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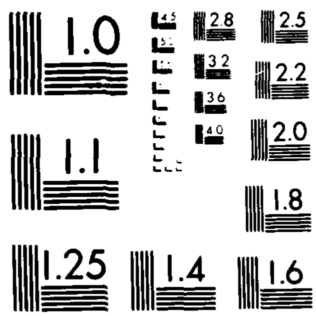

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T700 ENGINE CASE STUDY REPORT

(IDA/OSD R&M STUDY)

Paul F. Goree

IDA R&M Case Study Director

August 1983

Prepared for

Office of the Under Secretary of Defense for Research and Engineering

and

Office of the Assistant Secretary of Defense (Manpower, Reserve Affairs and Logistics)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document records the activities and presents the findings of the T700 Engine Case Study Report part of the IDA/OSD Reliability and Maintainability Study conducted during the period from July 1982 through August 1983.

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T700 ENGINE
CASE STUDY REPORT
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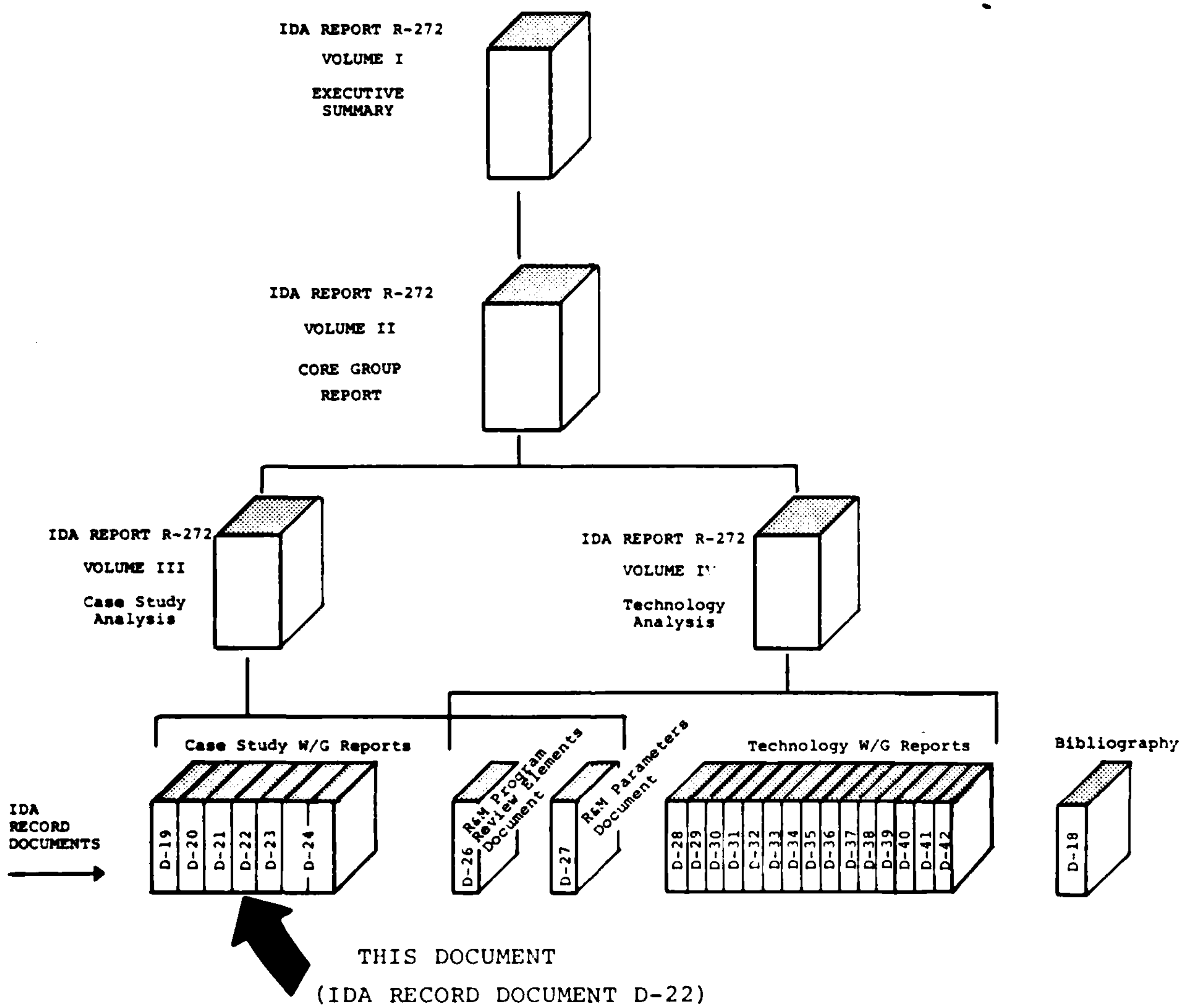
Paul F. Goree
IDA R&M Case Study Director

August 1983

INSTITUTE FOR DEFENSE ANALYSES
1801 N. Beauregard Street, Alexandria, Virginia 22311
Contract MDA 903 79 C 0018
Task T-2-126

RELIABILITY AND MAINTAINABILITY STUDY

— REPORT STRUCTURE —



PREFACE

As a result of the 1981 Defense Science Board Summer Study on Operational Readiness, Task Order T-2-126 was generated to look at potential steps toward improving the Material Readiness Posture of DoD (Short Title: R&M Study). This task order was structured to address the improvement of R&M and readiness through innovative program structuring and applications of new and advancing technology. Volume I summarizes the total study activity. Volume II integrates analysis relative to Volume III, program structuring aspects, and Volume IV, new and advancing technology aspects.

The objective of this study as defined by the task order is:

"Identify and provide support for high payoff actions which the DoD can take to improve the military system design, development and support process so as to provide quantum improvement in R&M and readiness through innovative uses of advancing technology and program structure."

The scope of this study as defined by the task order is:

To (1) identify high-payoff areas where the DoD could improve current system design, development program structure and system support policies, with the objective of enhancing peacetime availability of major weapons systems and the potential to make a rapid transition to high wartime activity rates, to sustain such rates and to do so with the most economical use of scarce resources possible, (2) assess the impact of advancing technology on the recommended approaches and guidelines, and (3) evaluate the potential and recommend strategies that might result in quantum increases in R&M or readiness through innovative uses of advancing technology.

The approach taken for the study was focused on producing meaningful implementable recommendations substantiated by quantitative data with implementation plans and vehicles to be provided where practical. To accomplish this, emphasis was placed upon the elucidation and integration of the expert knowledge and experience of engineers, developers, managers, testers and users involved with the complete acquisition cycle of weapons systems programs as well as upon supporting analysis. A search was conducted through major industrial companies, a director was selected and the following general plan was adopted.

General Study Plan

Vol. III • Select, analyze and review existing successful program

Vol. IV • Analyze and review related new and advanced technology

Vol. II (• Analyze and integrate review results
(• Develop, coordinate and refine new concepts

Vol. I • Present new concepts to DoD with implementation plan and recommendations for application.

The approach to implementing the plan was based on an executive council core group for organization, analysis, integration and continuity; making extensive use of working groups, heavy military and industry involvement and participation, and coordination and refinement through joint industry/service analysis and review. Overall study organization is shown in Fig. P-1.

The basic case study approach was to build a foundation for analysis and to analyze the front-end process of program structuring for ways to attain R&M, mature it, and improve it. Concurrency and resource implications were considered. Tools to be used to accomplish this were existing case study reports, new case studies

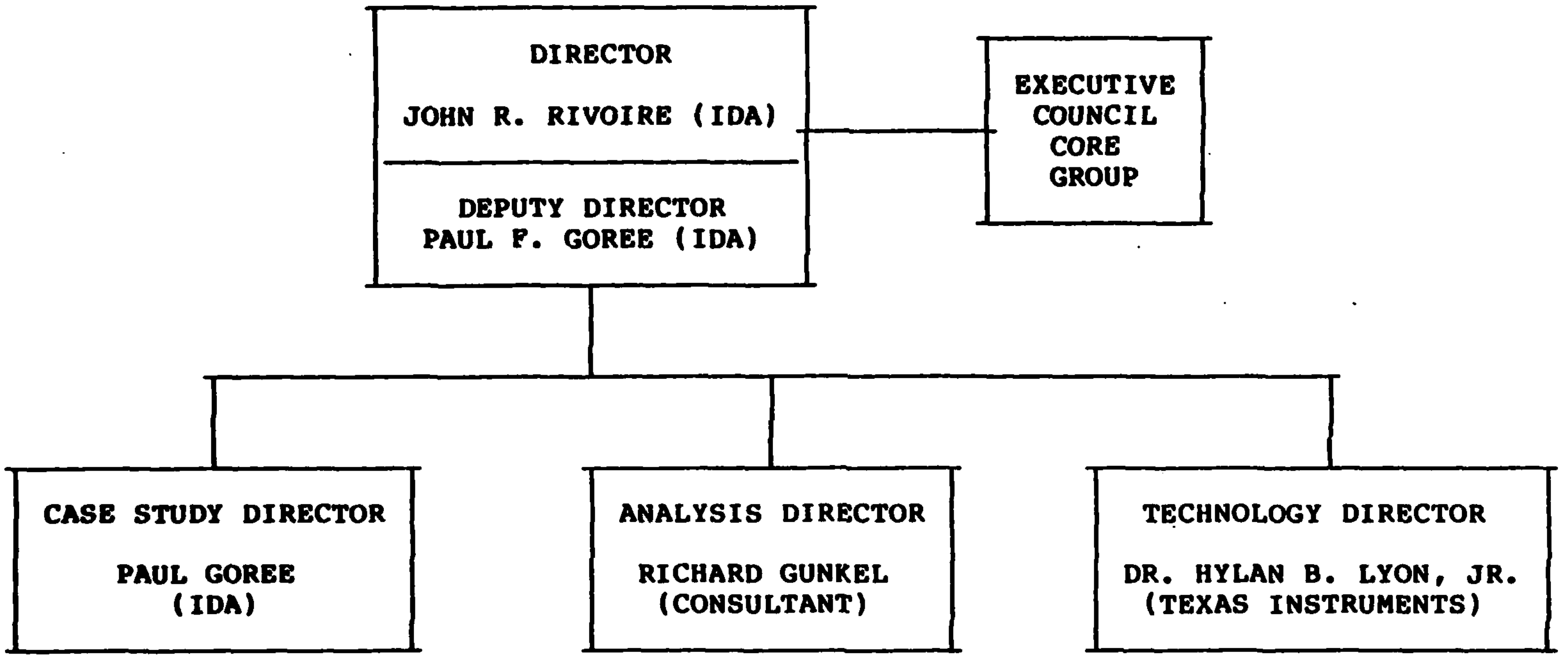


FIGURE P-1. Study Organization

conducted specifically to document quantitative data for cross-program analysis, and documents, presentations, and other available literature. In addition, focused studies for specific technology implications were conducted by individual technology working groups and documented in their respective reports. To accomplish the new case studies, the organization shown in Fig. P-2 was established.

In some areas where program documentation and records did not exist, the actual experience and judgement of those involved in the programs were captured in the case studies. Likewise, in the analysis process, the broad base of experience and judgement of the military/industry executive council members and other participants was vital to understanding and analyzing areas where specific detailed data were lacking.

This document records the program activities, details and findings of the Case Study Working Group for the specific program as indicated in Fig. P-2.

Without the detailed efforts, energies, patience and candidness of those intimately involved in the programs studied, this case study effort would not have been possible within the time and resources available.

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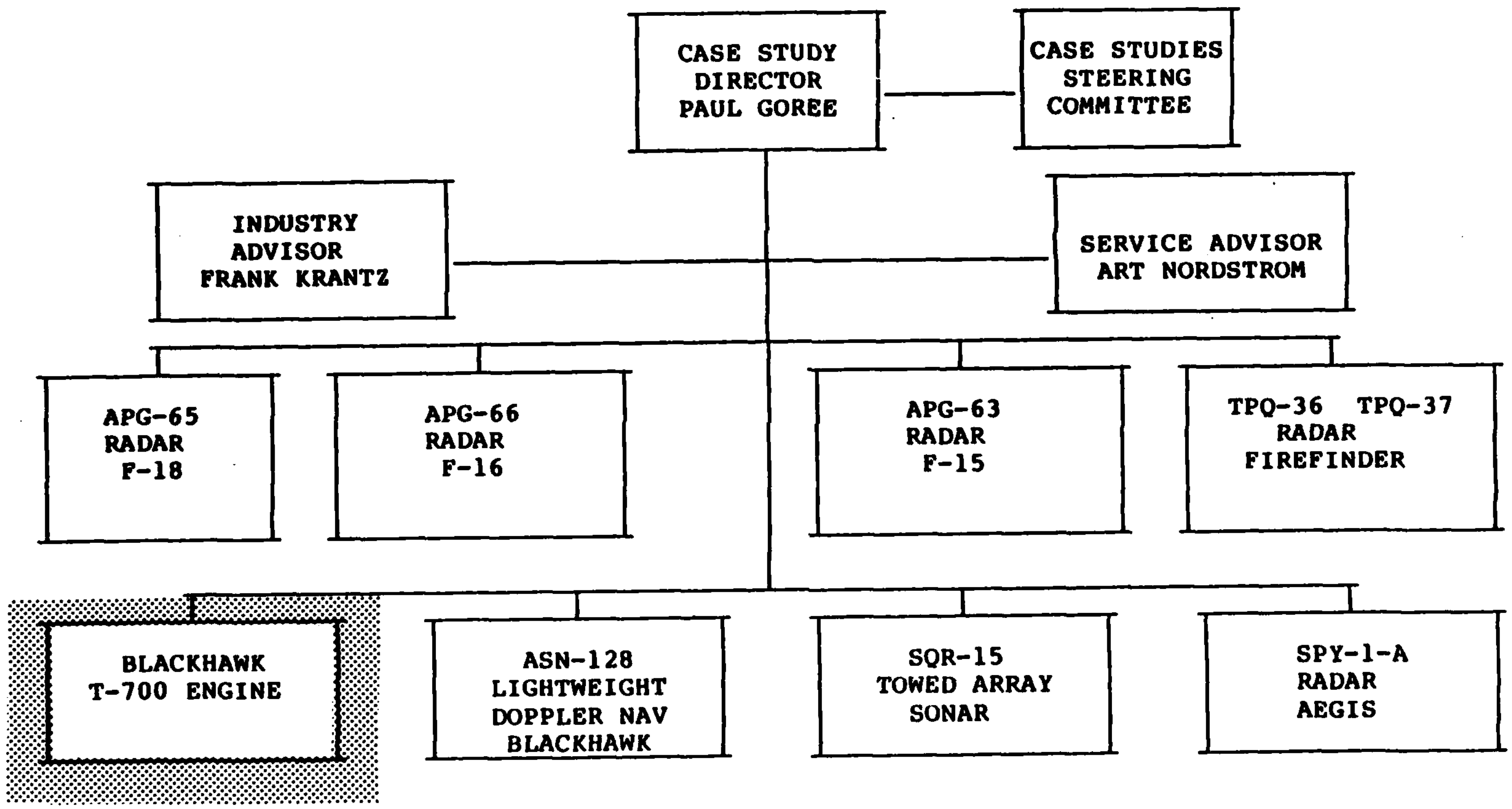

FIGURE P-2. Case Study Organization

BLACKHAWK T700 ENGINE

RELIABILITY AND MAINTAINABILITY CASE STUDY

FOREWORD

This case study represents an assessment of the predominant factors that most strongly influenced the outcome of the T700 Engine System Reliability and Maintainability Program.

Systems used within the military and identified as successful programs were selected for study to determine the factors that most strongly influenced the outcome of the programs. The case study was directed toward identifying program elements that were significant influencing factors on reliability and maintainability, documenting the lessons learned and establishing recommendations for future programs. This study, although directed specifically toward reliability and maintainability, encompassed a broad view of program elements and considered the complex interrelationship between contractual arrangements, management, design, manufacturing, and test and evaluation.

Reports documenting other case studies are published under separate cover. This report documents the case study of the T700 Engine used on the U.S. Army Black Hawk helicopter and other military as well as commercial applications.

T700 ENGINE WORKING GROUP

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BLACK HAWK PROGRAM MANAGER'S OFFICE

C. R. BROOKS - OFFICE OF DIRECTORATE FOR PRODUCT ASSURANCE

DARCOM

M. McINTYRE - INDUSTRIAL ENGINEER

IDA

P. F. GOREE - IDA DIRECTOR R&M CASE STUDIES

D. WEIDHUNER - CONSULTANT (FORMER MEMBER OF THE U.S. ARMY AVSCOM TEAM WHO WAS INSTRUMENTAL IN THE PREPARATION OF THE ORIGINAL UTTAS STATEMENT OF WORK (SOW) AND RFQ FOR THE UTTAS/1500 SHP GAS TURBINE ENGINE)

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3. Life Profile Establishment
4. R&M Failure Definition
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6. Source Selection Criteria
7. LCC Consideration

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24. Demonstration Testing
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GLOSSARY OF ACRONYMS

AMT	ACCELERATED MISSION TEST
ASMET	ACCELERATED SIMULATED MISSION ENDURANCE TEST
AAH	ADVANCED ATTACK HELICOPTER
ATE	ADVANCED TURBINE ENGINE
AVM	AIRFRAME VEHICLE MANUFACTURER
AVIM	AVIATION INTERMEDIATE MAINTENANCE
AVUM	AVIATION UNIT MAINTENANCE
BED	BASIC ENGINE DEVELOPMENT
BRACE	BAYESIAN RELIABILITY ANALYSIS COMPONENT EVAL.
BLM	BOTTON LINE MEASURE
CIP	COMPONENT IMPROVEMENT PROGRAM
CAD	COMPUTER AIDED DESIGN
CPIF	COST PLUS INCENTIVE FEE
DTC	DESIGN TO COST
DPR	DEVELOPMENT PROBLEMS REPORT
ECP	ENGINEERING CHANGE PROPOSAL
EFTC	EQUIVALENT FULL THERMAL CYCLE
ELCF	EQUIVALENT LOW CYCLE FATIGUE CYCLE
ETAMP	EQUIVALENT TIME AT MAX POWER
FETT	FIRST ENGINE TO TEST
FOD	FOREIGN OBJECT DAMAGE
GCT	GOVERNMENT COMPETITIVE TEST
GI	GROUND IDLE
GTV	GROUND TEST VEHICLE
HEX	HIGH ENERGY X-RAY
HMU	HYDROMECHANICAL UNIT
IPR	IN PROCESS REVIEW
IPS	INLET PARTICLE SEPARATOR
IP	INSTRUCTOR PILOT
ILS	INTEGRATED LOGISTIC SUPPORT
IRP	INTERMEDIATE RATED POWER
LCC	LIFE CYCLE COST
LCF	LOW CYCLE FATIGUE
LPDC	LYNN PRODUCT DATA CENTER
MI	MAINTENANCE INDEX
MC	MAXIMUM CONTINUOUS
MTBFRO	MEAN TIME BETWEEN FAILURE-REQUIRING OVERHAUL
MTBM	MEAN TIME BETWEEN MAINTENANCE
MTBR	MEAN TIME BETWEEN REMOVALS
MTBF	MEAN TIME BETWEEN FAILURES
MQT	MODEL QUALIFICATION TEST
MSR	MALFUNCTION SUMMARY REPORT
NCM	NUMERICAL CONTROLLED MACHINES
PEP	PRODUCIBILITY ENGINEERING PLANNING
PFRT	PRELIMINARY FLIGHT RATING TEST
PFRT	PRE-FLIGHT ROTATING TEST
PIDS	PRIME ITEM DEVELOPMENT SPECIFICATION
PPR	PROGRAM PROGRESS REVIEW
PMO	PROJECT MANAGER'S OFFICE
PTF	PATTERN TEMPERATURE FACTOR
QT	QUALIFICATION TEST
R&M	RELIABILITY AND MAINTAINABILITY
R/R	REMOVE AND REPLACE
RFP	REQUEST FOR PROPOSAL
RFQ	REQUEST FOR AUOTATION
SLS	SEA LEVEL STATIC
SVR	SHOP VISIT RATE
SMET	SIMULATED MISSION ENDURANCE TEST
SECT	SMALL ENGINE COMPRESSOR TEST
SPC	SPECIFIC FUEL CONSUMPTION
SOW	STATEMENT OF WORK
TBO	TIME BETWEEN OVERHAUL
DARCOM	US ARMY MAT'L DEVELOPMENT & READINESS COMMAND
UTTAS	UTILITY TACTICAL TRANSPORT AIRCRAFT SYSTEM

INTRODUCTION

INTRODUCTION

The General Electric T700-GE-700 is the main propulsion system on the U.S. Army's newest utility helicopter. The Sikorsky built UH-60A, Black Hawk. Derivative models of this engine also power the U.S. Army's newest Advanced Attack Helicopter; the Hughes-built AH-64, Apache; the latest U.S. Navy LAMPS Mark III system; the Sikorsky built SH-60B, Seahawk; and the Sikorsky-built HH-60D, Night Hawk for the USAF, which is currently under development.

The T700-GE-401 has also been selected for re-engining the Bell AH-1I Cobra for the U.S. Marine Corps. This attack helicopter has been designated the Super Cobra. The -401 engine has also been selected to power the Westland/Agusta EH-101 flight test aircraft.

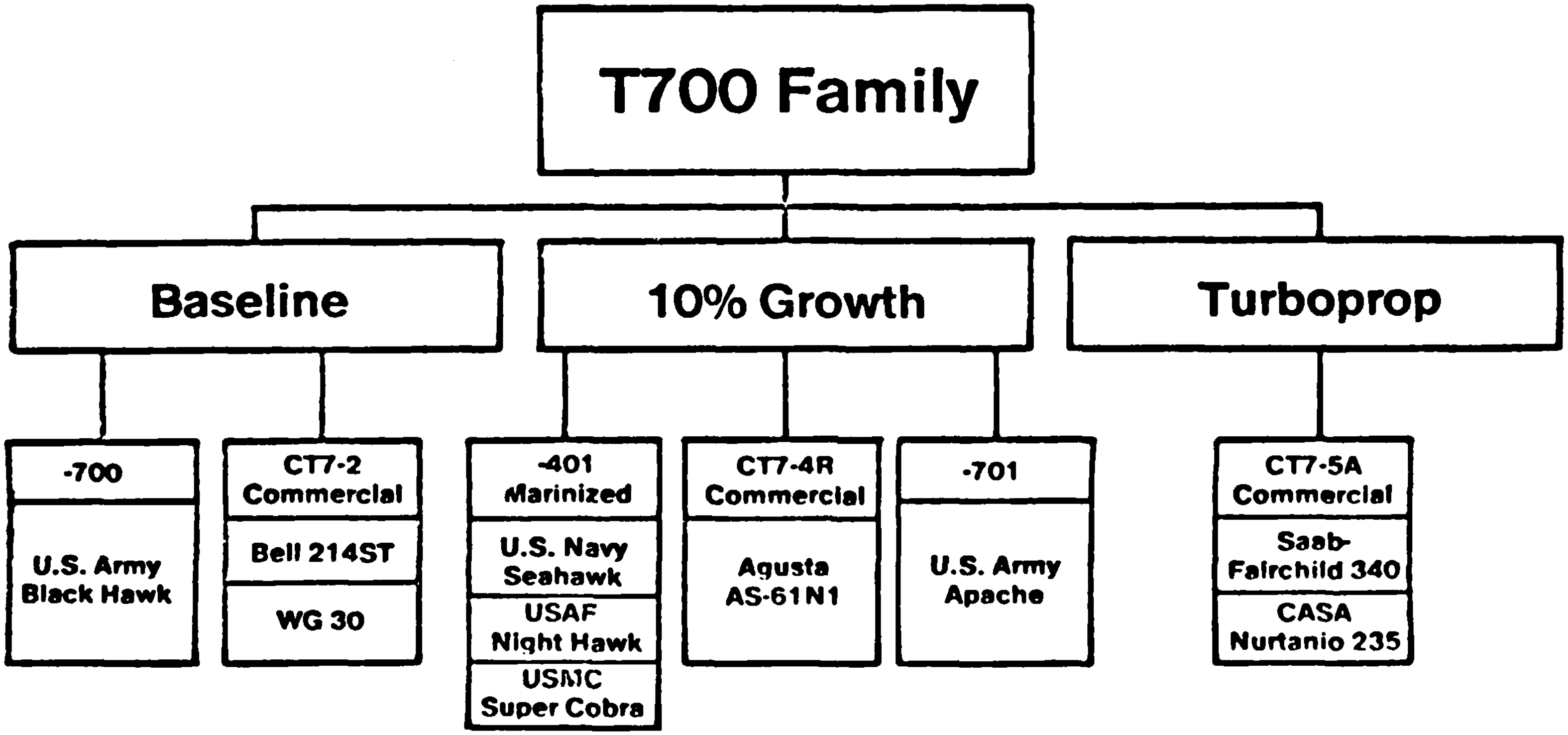
In addition to all of the military applications above, commercial models of the T700 engine designated the CT7-2A and -2B power the Bell 214ST and Westland WG-30 helicopters and a rear drive version of the CT7-4R is being considered by Agusta for re-engining the AS-61N1.

Turboprop versions of the T700 designated the CT7-5 and -7 are also being certified for the Saab-Fairchild S-F340 and the CASA-Nurtanio CN235 commuter aircraft.

Since introduction in the Black Hawk in 1979, the engine has accumulated over 300,000 flight hours and has established a record for reliability and maintainability in addition to fuel economy and ease of operation.

This report presents a description of the T700-GE-700 engine, describes the evolution of this turboshaft engine and discusses procedures and methodology which were executed during the development of this engine that were instrumental in achieving the R&M goals which were established by the U.S. Army at the outset of this program.

The many lessons learned during this program are also summarized as a guide for future turboshaft engine development programs.


T700 Family
Baseline
10% Growth
Turboprop
-700
U.S. Army Black Hawk
CT7-2 Commercial
Bell 214ST
WG 30
-401 Marinized
U.S. Navy Seahawk
USAF Night Hawk
USMC Super Cobra
CT7-4R Commercial
Agusta AS-61N1
-701
U.S. Army Apache
CT7-5A Commercial
Saab-Fairchild 340
CASA Nurtanio 235

INTRODUCTION

- MISSION NEEDS
- SYSTEM DESCRIPTION
- PROGRAM SUMMARY
- MEASURES OF SUCCESS

MISSION NEEDS

1960s Message From the Field

Improve Engine Reliability and Maintainability

T700-707(120682)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

MISSION NEEDS

U.S. Army Concept Formulation Studies of a replacement for the UH-1 "Huey" transport helicopter began in the mid-sixties. Aircraft system characteristics and requirements were defined, which would represent a notable advance in the state-of-the-art for airframe and engines. These characteristics were determined, in part, by experience with the generation of helicopters which were accumulating hundreds of thousands of hours in the Southeast Asian war zone.

The concept of dependable, effective troop deployment via helicopters became rapidly ingrained in modern battlefield strategy. But combat experience identified a need for additional "hot day" performance capabilities, significantly improved aircraft and engine reliability and easier flight-line maintainability.

For example, it was discovered that fuel cost at operational forward areas could often reach $5.00 or more per gallon! Maintenance and logistic support were severe problems and nearly 60% of all unscheduled UH-1 engine removals were caused by ingestion of foreign objects and sand erosion. In addition, the manpower squeeze began to severely tax available resources for maintenance and inspections.

Another important consideration was improved survivability required for mid-intensity combat situations. Survivability not only includes ability to survive projectile damage and either complete the mission or return home safely, but also includes the need for total crew crash protection by use of energy absorbing aircraft structure and fire-proof engine fuel systems.

Field commanders also recognized a big potential payoff for increased aircraft survivability by avoiding or minimizing detection by the enemy. Thus, aircraft survivability became synonymous with flying close to the surface (Nap-of-the-Earth), tight maneuver capability, noise suppression and minimal radar reflectivity.

These recognized needs were quantified by the Department of the Army and an RFP was issued to the helicopter industry in late 1971.

The Army's requirements for UTTAS (Utility Tactical Transport Aircraft Systems) included twin engines and capability for lifting a crew of three plus 11 combat equipped troops out of ground effect at a 4000 ft. altitude, 95°F.

As an integral part of the UTTAS Program, the engine design had to reflect key aircraft concerns for system survivability, reliability and maintainability.

Unlike UTTAS Program requirements which were propagated by Vietnam experience, the Advanced Attack Helicopter (AAH) was a result of a tactical necessity for an anti-tank attack helicopter that could survive in a mid-intensity battlefield environment. Army management recognized that low speed maneuverability and Nap-of-the-Earth flight capability under all types of weather conditions were essential to minimize detection and, hence, enhance aircraft survivability. In addition, advanced design techniques could considerably toughen the AAH, allowing it to absorb projectile hits and keep performing effectively. Other key conceptual requirements included sizing the propulsion system for maximum firepower payload at altitude, hot day conditions and minimizing Life Cycle Cost by meeting appropriate reliability and maintainability objectives.

- UTTAS/AAH ENGINE MISSION NEEDS:
    - 1500 SHAFT HORSEPOWER WITH IMPROVED HOT DAY PERFORMANCE.
    - 20-30% REDUCED FUEL CONSUMPTION.
    - 37-50% REDUCED MAINTENANCE MAN HOURS.
    - IMPROVED RELIABILITY.
    - IMPROVED SURVIVABILITY.
    - INTEGRAL INLET PARTICLE SEPARATOR.
    - REDUCED LOGISTICS SUPPORT.

ENGINE DESCRIPTION

ENGINE DESCRIPTION

The T700-GE-700 was designed to meet the overall requirements of performance, reliability, maintainability, safety, vulnerability and costs of ownership set down in the RFP. In addition, General Electric imposed firm design-to-cost goals and programs to control initial acquisition costs.

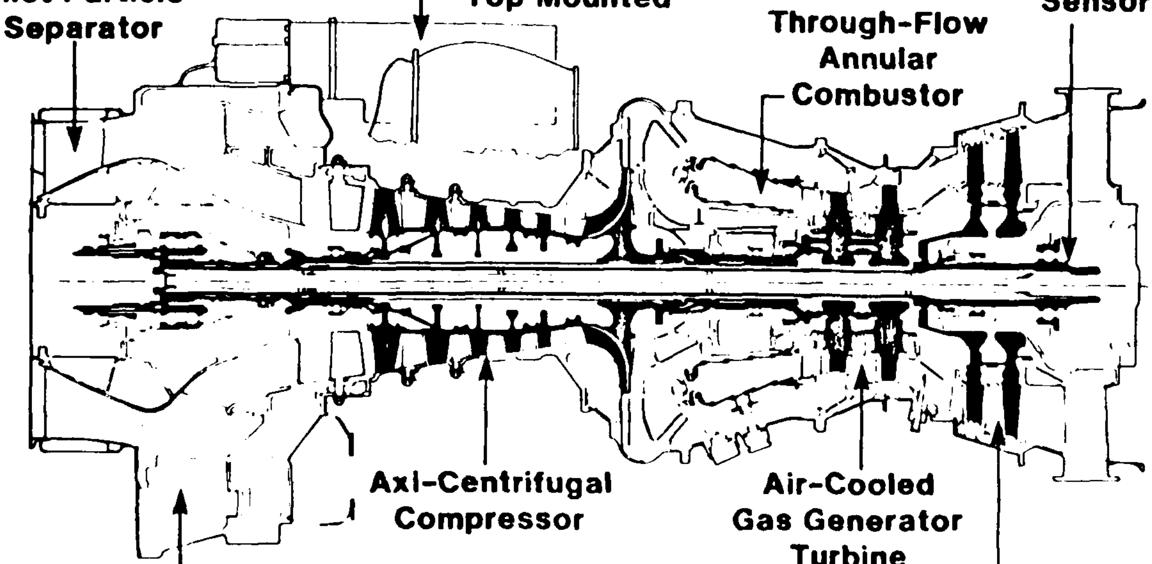
Consistent witht the overall design requirements it was judged by the U.S. Army and GE that the design weight of the engine should include those features essential to achieving the technical, operational and economic objectives. The T700 engine weight includes, as a consequence, many design features such as the Inlet Particle Separator, Integral Oil Tank, Emergency Lube System, Modular Design and Condition Monitoring/Diagnostic provisions which are not traditionally engine accountable.

Performance emphasis was placed on achieving high power plus good part-power SFC. Based on its sea-level, standard day output, the T700 develops about 3.84 horsepower per pound. (Reference Page IB-5).

The engine is a single-spool core, front drive turboshaft engine. It has fewer parts than any of today's comparable horsepower class engines. It features modular construction throughout and functions as a self-contained unit with many systems previously required as part of the airframe equipment.

It has a completely integral and anti-iced inlet particle separator (IPS) plus a self-contained lubrication system with emergency loss of oil provisions including oil tank and oil cooler. The engine features condition monitoring and diagnostic maintenance provisions, has self-contained electrical ignition and control power systems and an engine-driven fuel boost pump for suction fuel capability. The water-wash system and separator are integral.

Basic Design



T700-7(103079)

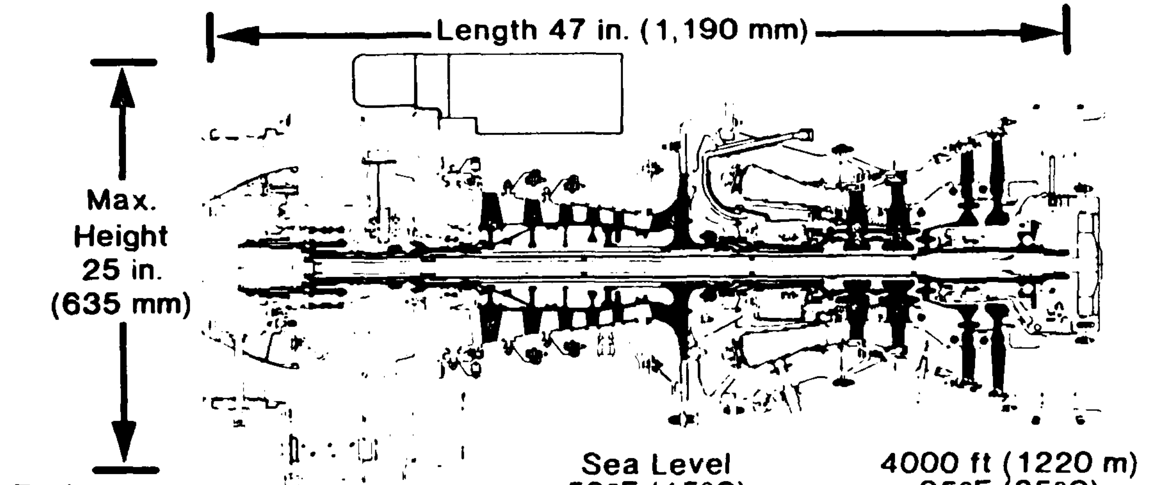
The cold section module contains three frames as part of the IPS structure, which also doubles as the oil tank, front mount and accessory gearbox support. The compressor consists of a five-stage, transonic, axial flow compressor and a single-stage centrifugal compressor connected in series and affixed to the same shaft. The axial compressor consists of four blisks (integrally bladed disks) with stages 3 and 4 machined on the same blisk.

The engine's hot section module consists of a two-stage air-cooled gas generator system, and a through-flow annular combustor. This low pressure, in-line combustor design was selected as offering the best operating characteristics for the US Army helicopter applications: high reliability, durability, low vulnerability, high performance, proven PTF and gas temperature profile control, and low exhaust emissions. The machined-ring approach for the combustor shells was purposely selected over the conventional, lower-cost, fabricated constructions because of the requirement to provide a long-life hot section. The air-cooled gas generator turbine operates at temperature levels consistent with long life while providing maximum efficiency and 25 percent lower fuel consumption, particularly at part-power operation. The hot section life of the engine is deliberately planned to improve overall operating reliability.

The power turbine module consists of the independent, two-stage uncooled, low-pressure turbine. The low-pressure turbine shaft, which has a rated speed of 20,000 rpm, is coaxial and extends to the front end of the engine where it is connected to the AVM output shaft. There are a total of three sumps, two high-pressure turbine rotor bearings and four low-pressure turbine rotor bearings.

A more detailed description of engine subsystems is contained in the Appendix of this report.

T700-GE-700 Specifications

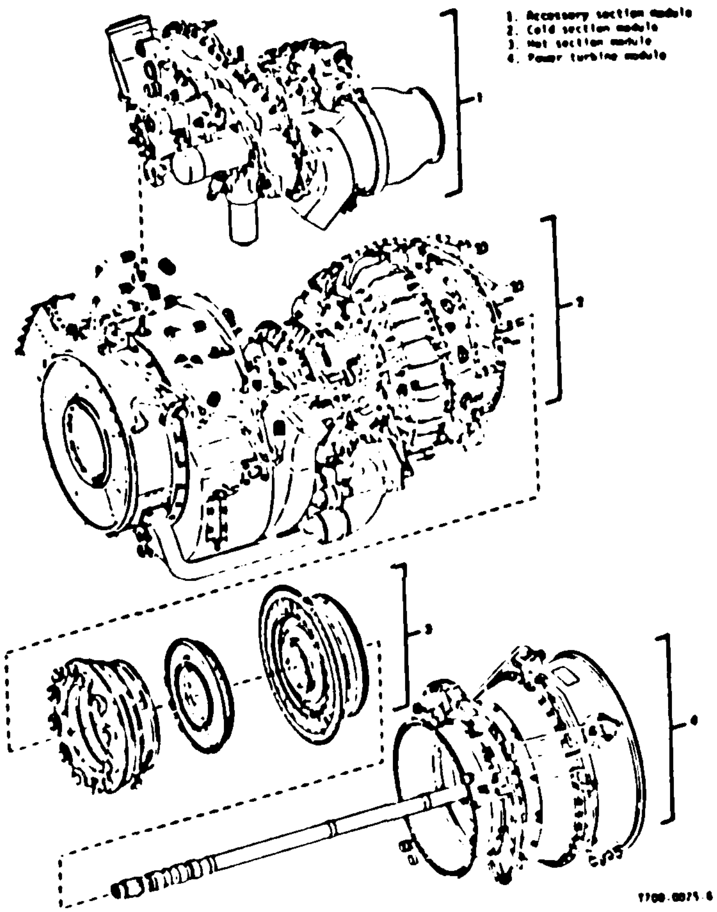


Rating	Sea Level 59°F (15°C)	4000 ft (1220 m) 95°F (35°C)
● Intermediate (30 minutes)		
SHP	1,560 (1,164 kw)	1,179 (879 kw)
SFC	.464 (.282*)	.478 (.291*)
● Cruise Power		
SHP	900 (671 kw)	
SFC	.520 (.316*)	
● Weight 423 lb (192 kg)		

(*Values in kg/kw-hr)

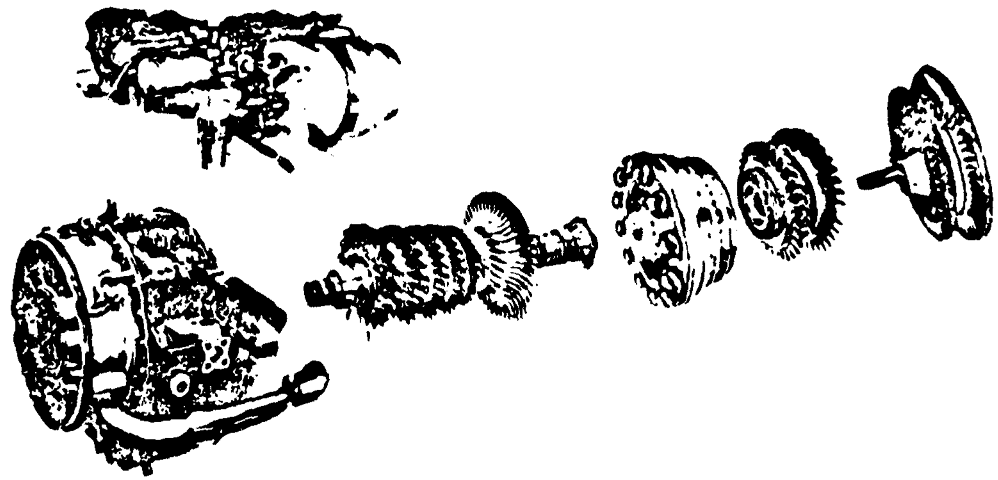
T700-927(091481)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP



Modular Construction

T700 Design Basis



- Combined U.S. Army/General Electric Experience
- Advanced but Fully Developed Technology
- Reliable/Long Life
- Simplified Pilot Control
- Optimized Cruise Fuel Consumption
- Simplified Maintenance
- Low Life Cycle Cost

T700-1185(3-79)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

T700 Engine
Features Summarized

- Low Fuel Consumption — Optimized for Cruise
- Built for the Environment
  - Integral Sand Separator
  - Built-in Compressor Cleaning
  - Rugged Compressor
- Simplified Pilot Control
- Reduced Maintenance Workload
  - No Adjustments
  - 10 Standard Tools for all Unit and Intermediate Maintenance
  - High Reliability/Long Life

T700-1158(6-78)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

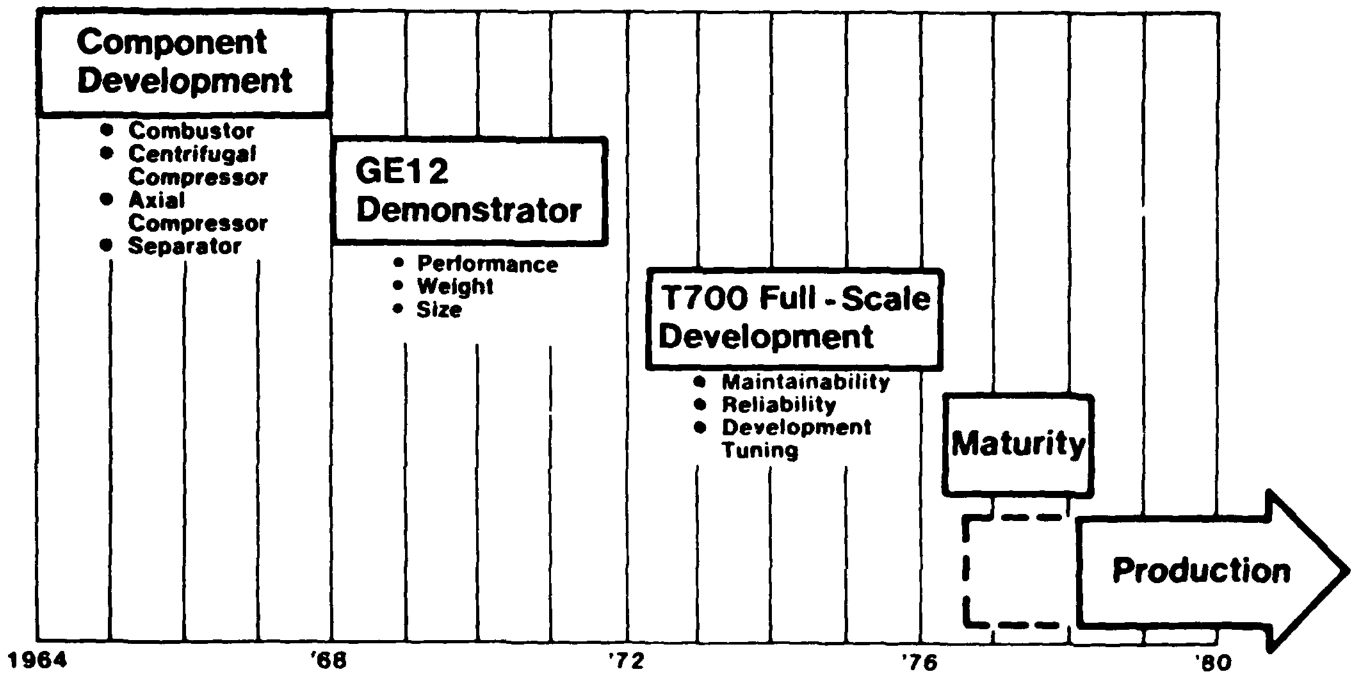
PROGRAM SUMMARY

T700 ENGINE PROGRAM SUMMARY

The design and development of the T700-GE-700 turboshaft engine started with early component development work in 1964 and culminated with the shipment of the first production T700 engine in March, 1978. Highlights of the overall program structure are as follows:

- Early Component Development.
- Demonstrator Program.
- Full Scale Design/Development/Qualification Program
  - Development of Statement of Work/Prime Item Development Specification SOW/PIDS
  - Initial Design/Hardware Release
  - Development/Qualification Test Program
  - AVM's Basic Engine Development/Government Competitive Test (BED/GCT)
- Maturity Program/Production Transition.
- Production/Fielding.

Engine Evolution



T700-549(9-77)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

To reduce risks for a new aircraft gas turbine engine much preliminary design work accompanied by research and development type component testing was felt to be necessary well in advance of combining components into a full prototype demonstrator engine. As early as 1964, component test programs were initiated on advanced annular combustors with improved pattern factors (PTF) aimed at more efficient combustion with no visible smoke. In addition, research and development work was conducted on both axial and centrifugal advanced design compressors aimed at higher efficiencies and increased stall margin.

Highly instrumented compressor test vehicles were assembled and tested in the small engine compressor test (SECT) facility. A special centrifugal compressor test stand was also utilized for testing advanced design centrifugal compressor models. In addition, a special test facility was constructed to test the inlet particle separator as a component so that configurations could be tested in a short period of time and the design optimized before being installed on an engine.

This early component development testing provided a technology base upon which to design a new engine and was the basis for the design of the GE12 demonstration engine.

In order to establish the feasibility of a new engine with the required characteristics, an Army-sponsored Competitive Advanced Technology Demonstrator Program was launched in 1967. General Electric's entry, the GE12, was designed to meet the new requirements. It featured a five-stage axial compressor followed by a single centrifugal stage, providing about a 15:1 pressure ratio. Its combustor, a straight through annular design, utilized central fuel injectors. The two-stage, air-cooled gas generator turbine was designed to meet both reliability and life requirements of the U.S. Army and was based upon GE commercial and military high temperature turbine experience. The two-stage power turbine was a simple, uncooled design constructed from proven materials. The GE12 design was aimed at several simultaneous goals, featuring performance and long life. It was to demonstrate these features by achieving:

a) 1500 SHP output power

b) .50 SFC @ 900 HP

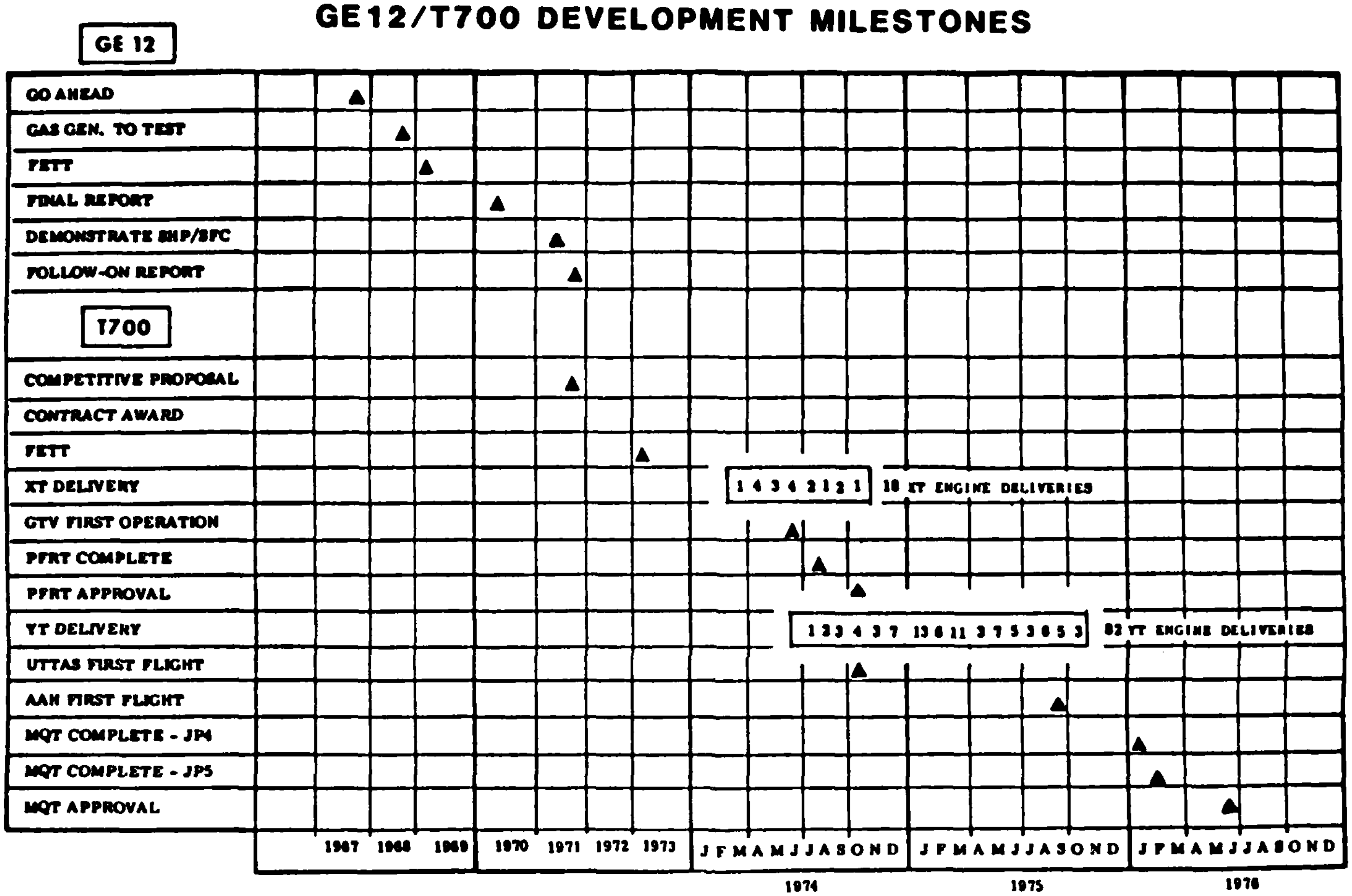
c) A simple, rugged design

d) Engine weight improvement of 40%

The performance and weight achieved by the GE12 closely matched the objectives of the U.S. Army AVLABS demonstrator program. In addition, 373 engine test hours were achieved and nearly 9500 component test hours were run.

The results of this demonstrator program provided assurance that a high performance, reliable propulsion system could be developed.

GE12/T700 DEVELOPMENT MILESTONES

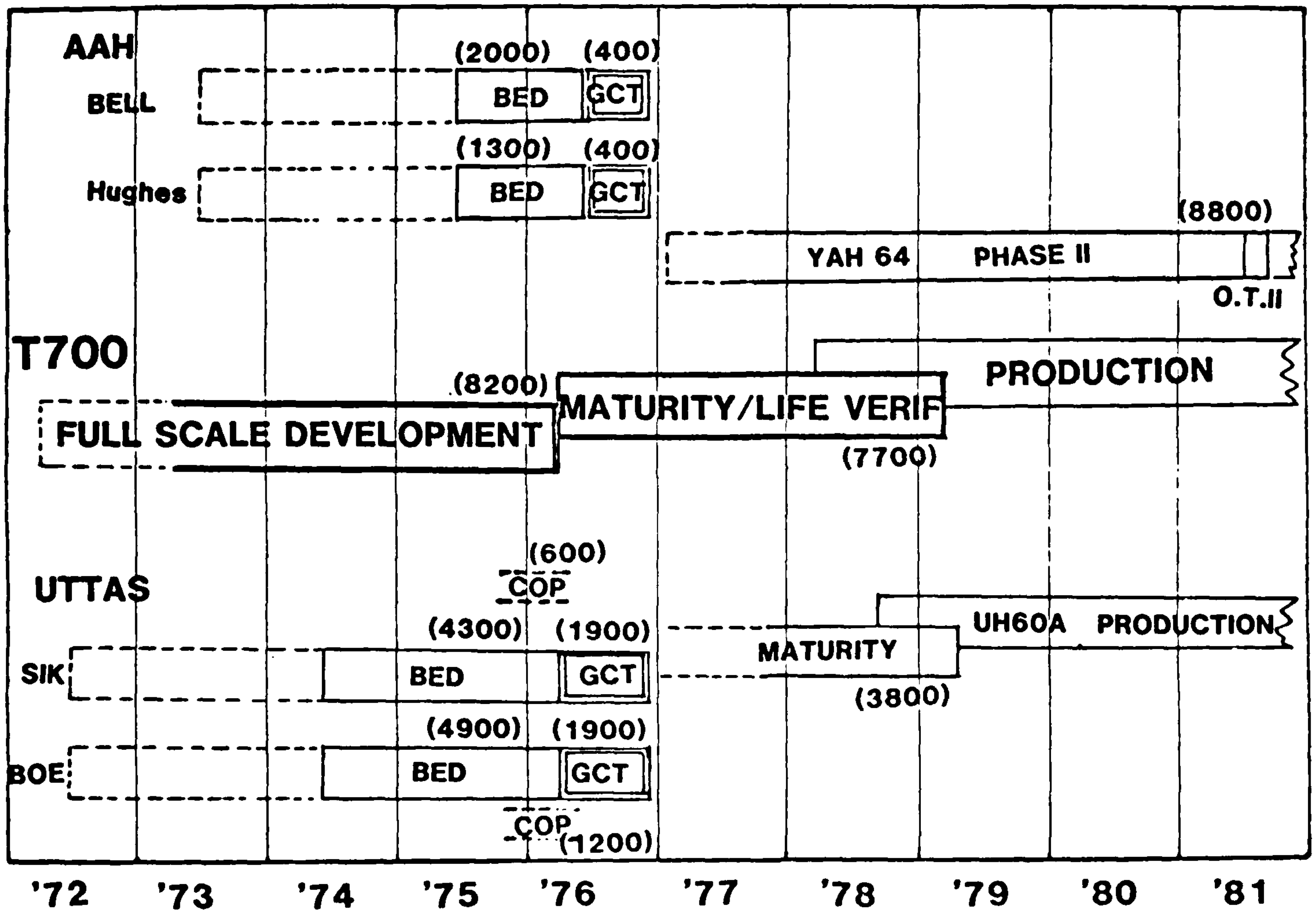


In September 1971 the GE12 engine was proposed - with some minor modifications and the addition of the Integral Inlet Separator - in response to an Army RFP for the 1500 SHP UTTAS powerplant. In December 1971 this engine, now designated T700-GE-700, was selected. The development contract was awarded in March of 1972. Major contract was awarded in March of 1972. Major contract features included full development and production qualification of the engine and support of the UTTAS competitive aircraft manufacturers. Many of the design features of the T700 were taken directly from the GE12.

The development program began with a contract award (Contract #DAA201-72-C-0381) in March of 1972. The first engine went to test less than one year later and began a fourteen-engine build-up of testing, which surpassed 8000 factory hours. The development included completing twenty separate official QT tests. 140,000 hours of component testing were also accumulated. With the second 150-hour endurance test completed and laid out, all required model qualification requirements were achieved by the contracted 31 March 1976 date.

In the second quarter of 1974 the engine began a series of field and flight tests. On four ground test vehicles, eighteen XT700 engines accumulated over 8000 hours. A sampling and inspection plan was established to provide rapid advancement of allowable operating times. The objective was to advance the engine to a true on-condition maintenance without a specified TBO removal. After 350 hours of GTV operation, XT engines were released for on-condition overhaul. This concept worked well and resulted in high-time engine experience. The four high-time XT field engines accumulated 60 to 1000 hours with one engine, XT4, having exceeded 1050 hours, of which 880 hours were continuous operation in one installation.

T700/BLACK HAWK/APACHE DEVELOPMENT PROGRAM



UTTAS Flight Testing began in the fourth quarter of 1974. The eighty-two YT engines shipped were used to support a total of twelve UTTAS and AAH Flight Test Vehicles. Over 16,000 engine hours were accumulated through 1978 in the UTTAS program's ground and flight tests. AAH flight testing began in the third quarter of 1975 and accumulated over 4300 ground and flight test engine hours through 1982.

When the development and flight test programs are combined with an additional 7700 hours during Maturity Testing through 1979, the cumulative total of T700-GE-700 experience was over 35,000 hours when the first production engine was shipped in March 1978.

Since the first production engine was shipped, 1000 engines have been provided to the Black Hawk Program with over 400 Black Hawks having been delivered through June 1983.

During this four (4) year period, the engines have accumulated over 300,000 flight hours and have been subjected to environments, including the desert sands of Egypt, the tropical jungles of Panama and the arctic clime of Ft. Greely, Alaska, with remarkable reliability and trouble-free operation.

This report summarizes the methodology applied during this program which has resulted in the Reliability and Maintainability achieved by the T700-GE-700 engine to date.

T700 ENGINE PROGRAM MILESTONES SUMMARY

- RFQ ISSUED BY U.S. ARMY IN JULY, 1971 FOR 1500 SHP GAS TURBINE ENGINE FOR UTTAS.
- GENERAL ELECTRIC SUBMITTED PROPOSAL IN SEPT. 1971, BASED ON GE12 DEMONSTRATOR DESIGN.
- U.S. ARMY SELECTED GE'S PROPOSAL IN DECEMBER 1971.
- FULL SCALE DEVELOPMENT AWARDED IN MARCH 1972, TO DEVELOP/QUALIFY THE T700-GE-700 GAS TURBINE ENGINE.
- FIRST-ENGINE-TO-TEST (FETT) IN FEBRUARY 1973.
- T700 QUALIFIED ON SCHEDULE IN MARCH 1976.
- UTTAS AND AAH FLIGHT TEST PROGRAMS CONDUCTED IN PARALLEL WITH T700 DEVELOPMENT.

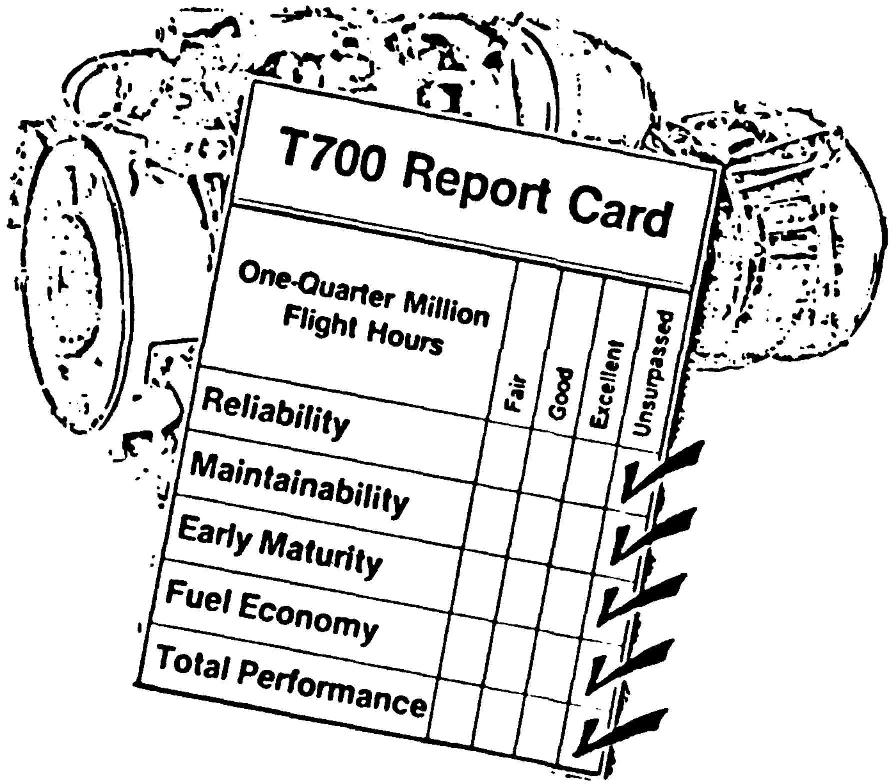
T700 Program Status

- Selected For 11 Major Aircraft Systems
  - 6 Civil Applications
  - 5 Military Applications
- Over 1000 Production Engines Delivered
- Production Rate at 35 Engines/Month
- Over 1/4 Million Field Service Hours
- Outstanding Field Service Demonstrated

MEASURE OF SUCCESS

MEASURES OF SUCCESS

The real "Measure of Success" of how well reliability and maintainability have been 'designed-in' to an aircraft gas turbine engine like the T700-GE-700 comes when the helicopter and engines are finally turned over to the eventual user and put into operation in the field under actual environmental conditions. The T700 powered Black Hawk was first introduced into the U.S. Army inventory at Ft. Rucker in April 1979, and during the past four years over 400 Black Hawks have been put into service. The 1000th T700 engine was shipped in June 1983. During this four year period, this engine has accumulated approximately 300,000 flight hours and has compiled an unprecedented record for reliability and maintainability, resulting in significant reductions in operating costs for the U.S. Army.



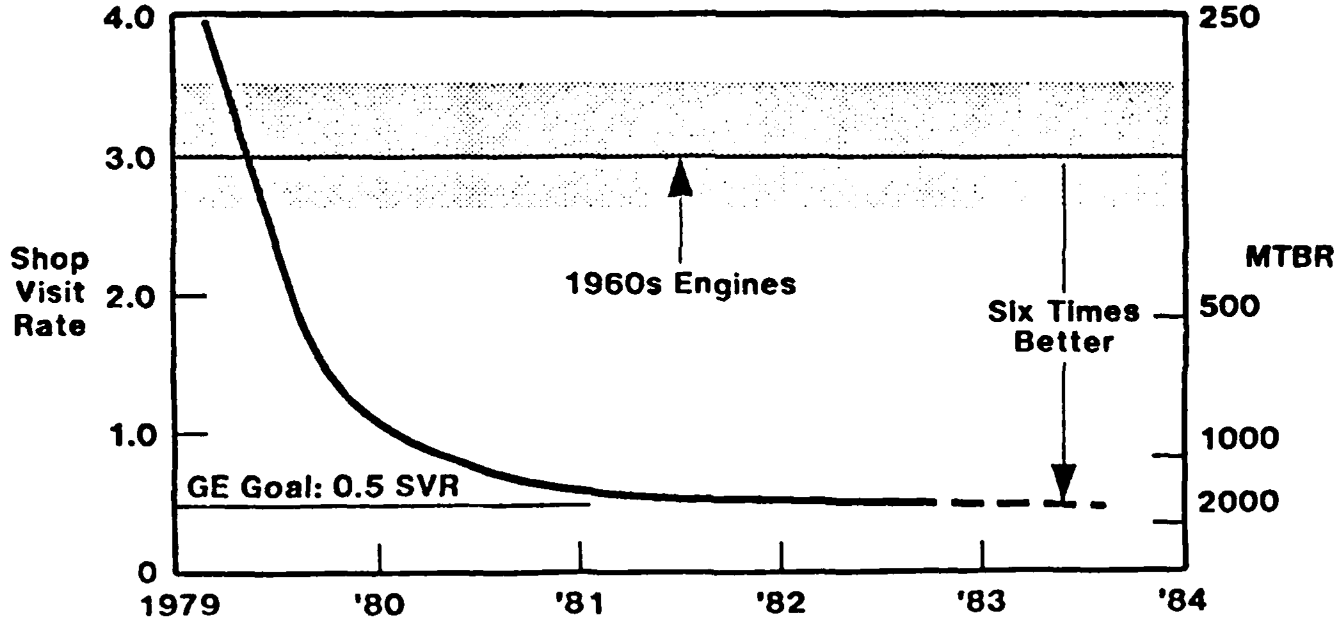
T700 Report Card
One-Quarter Million Flight Hours
Fair
Good
Excellent
Unsurpassed
Reliability
Maintainability
Early Maturity
Fuel Economy
Total Performance

One of the most meaningful measures of reliability for an aircraft gas turbine engine is how often the engine is required to be removed from the helicopter for maintenance. This removal rate has been designated in aviation circles as Mean Time Between Removals (MTBR), which is determined by dividing the total flight hours for a given period by the number of engine removals requiring maintenance. The reciprocal of the MTBR is the rate of engines removed per 1000 flight hours requiring maintenance at some level and this index has been designated by General Electric as Shop Visit Rate (S.V.R.). As may be noted on the T700 Shop Visit Rate chart, the T700 engine has averaged just under 0.70 removals per 1000 flight hours for all causes over the first *four years in service for an* MTBR *of* 1435 hours for all causes including F.O.D. compared to the experience in Southeast Asia on 1960 vintage engines MTBR's which run between 300-400 hours (Reference Page ID-7). The Shop Visit Rate (S.V.R.) on the T700 engine in 1982 was 0.48 for all causes including F.O.D. for an MTBR of almost 2100 hours or approximately a six times improvement in engine reliability.

If only chargeable engine caused removals are considered, the S.V.R. for 1982 was 0.21 for an MTBR for engine caused problems of over 4700 flight hours.

T700 Shop Visit Rate

T700 Achieving Excellent Reliability



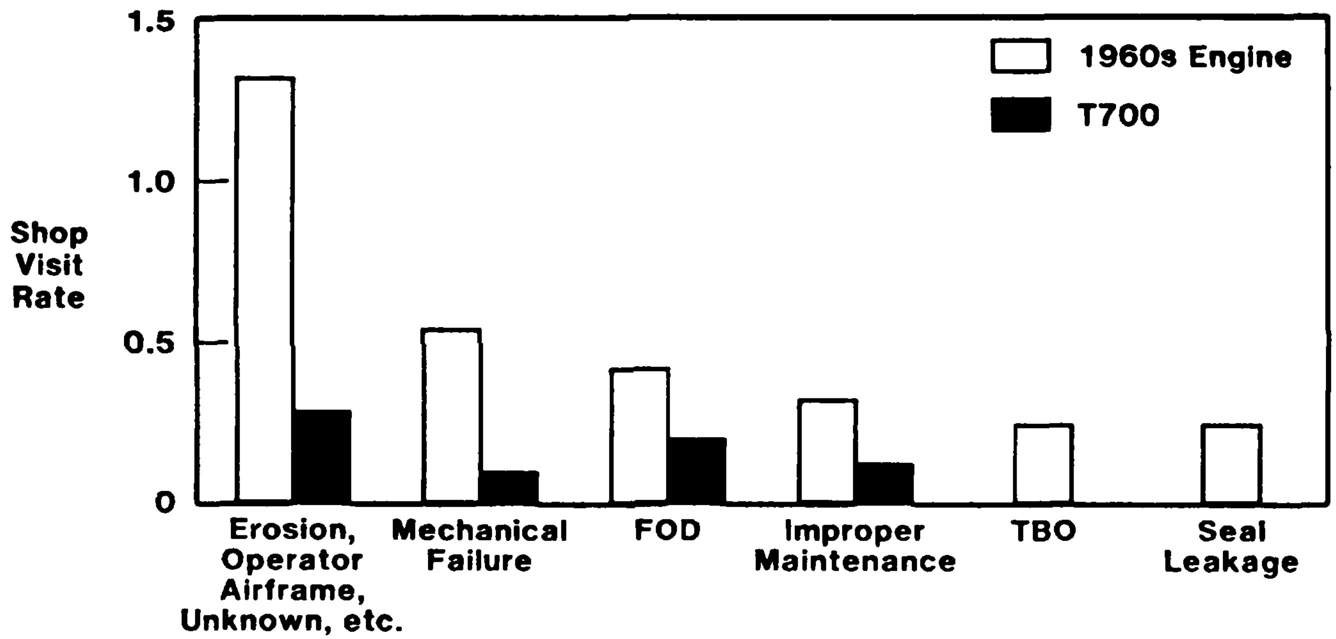
Average First Quarter Million Hours — 0.67 SVR!

T700-776(121382)

During the first four years of T700 operations in the Black Hawk, Army mechanics and crew chiefs have reportedly been impressed with the *minimum maintenance* required by the T700 engine. With no scheduled removals for hot section inspections or scheduled overhauls, coupled with the inherent reliability of the engine and accessories, flight line and intermediate maintenance workloads have been significantly reduced. (Reference Page ID-8.)

It has been calculated that all the maintenance required *on* the flight line by the T700 engine during the first four years of service could have been done by one mechanic. This is a true measure of the maintainability of an engine and is the result of efforts by both the U.S. Army's Project Manager's Office (PMO) and the Contractor to assure that *maintainability* was given equal priority to the other parameters during the development of this engine.

Shop Visit Rate Comparison

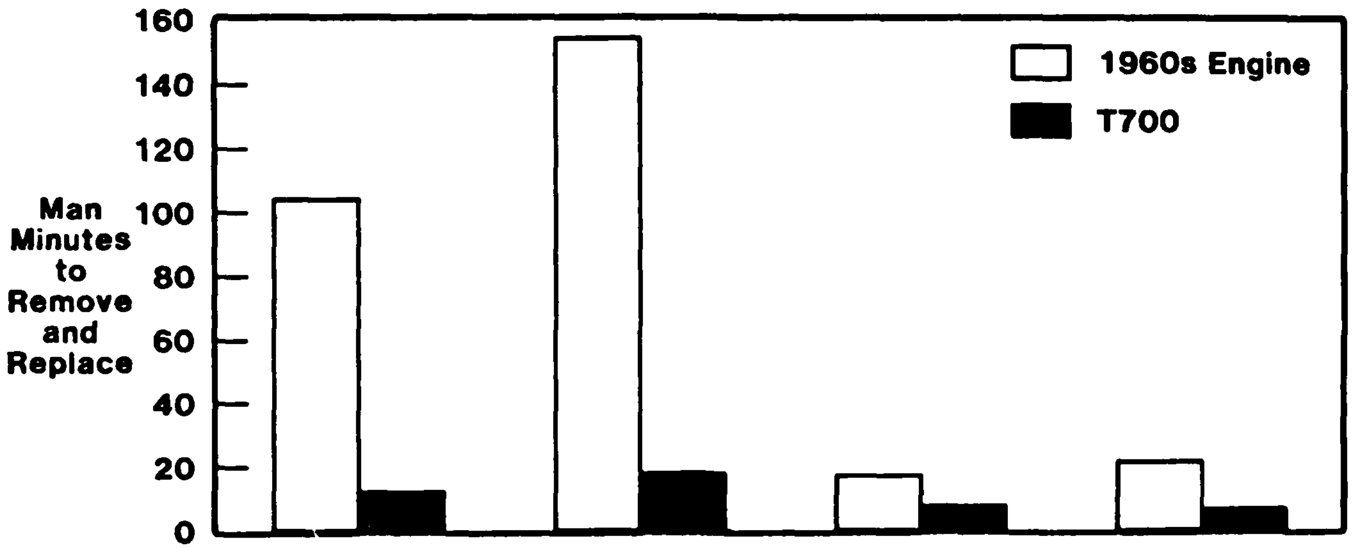


Vastly Improved Reliability — Meeting Design Objectives

T700-713(121082)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

Flight Line Maintainability Comparison



	Fuel Control	Fuel Manifold	Igniter Plug	AI/SB Valve
• T700				
— Required (MM)	22.0	—	9.0	7.0
— Actual (MM)	13.0	20.0	7.4	6.3

T700-714(121082)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

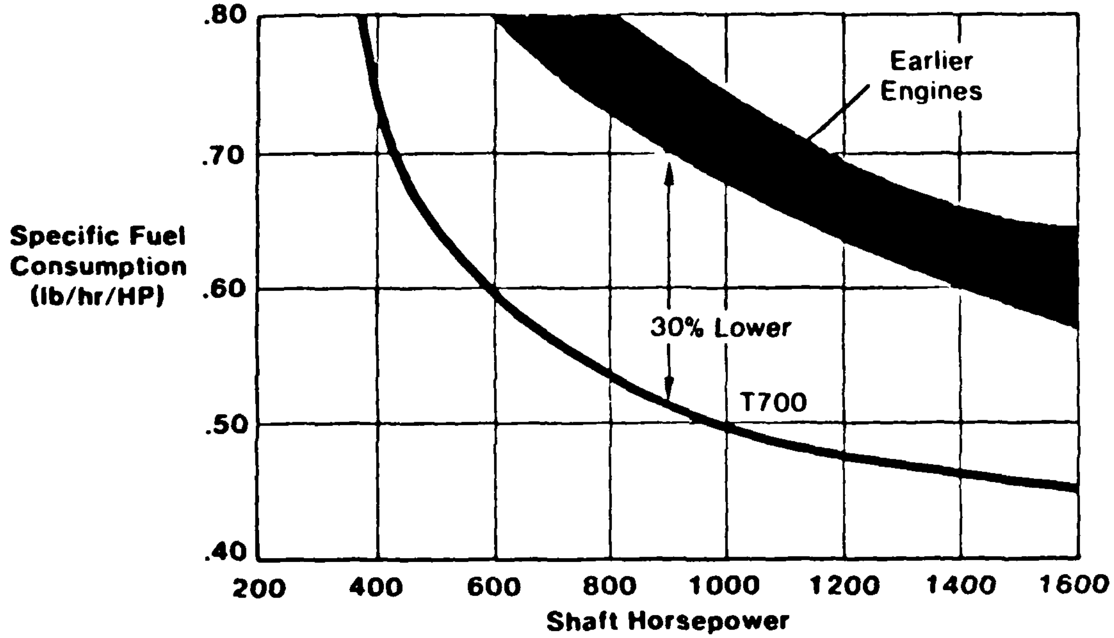
Pilots who have flown the Black Hawk have been impressed with the low fuel consumption of the T700 engines. Remarks by IP's at Ft. Rucker indicated the twin engines on the Black Hawk use little more fuel during a one hour flight than is used by a Huey with a single engine on a one hour flight. (Reference Page ID-10)

Comparisons of fuel consumption will vary depending on the engine and aircraft being considered but on an average basis, the Specific Fuel Consumption (S.F.C.) on the T700 engine is from 15 to 30% better than helicopter engines of the 1960 vintage. As shown on ID-10, an improvement of 30% can result in a significant savings in fuel costs over 5000 hours of operation.

One of the most important 'measures of success' of an aircraft gas turbine engine is how much does the engine cost the user over the expected useful life of the system. This total cost is referred to as Life Cycle Cost (LCC). (Reference Page ID-11)

As a result of the priorities given by both the U.S. army and the Contractor to both *reliability and maintainability*, the T700 engine provides a significant reduction in Life Cycle Costs, as compared to previous engines, as shown on Page ID-11.

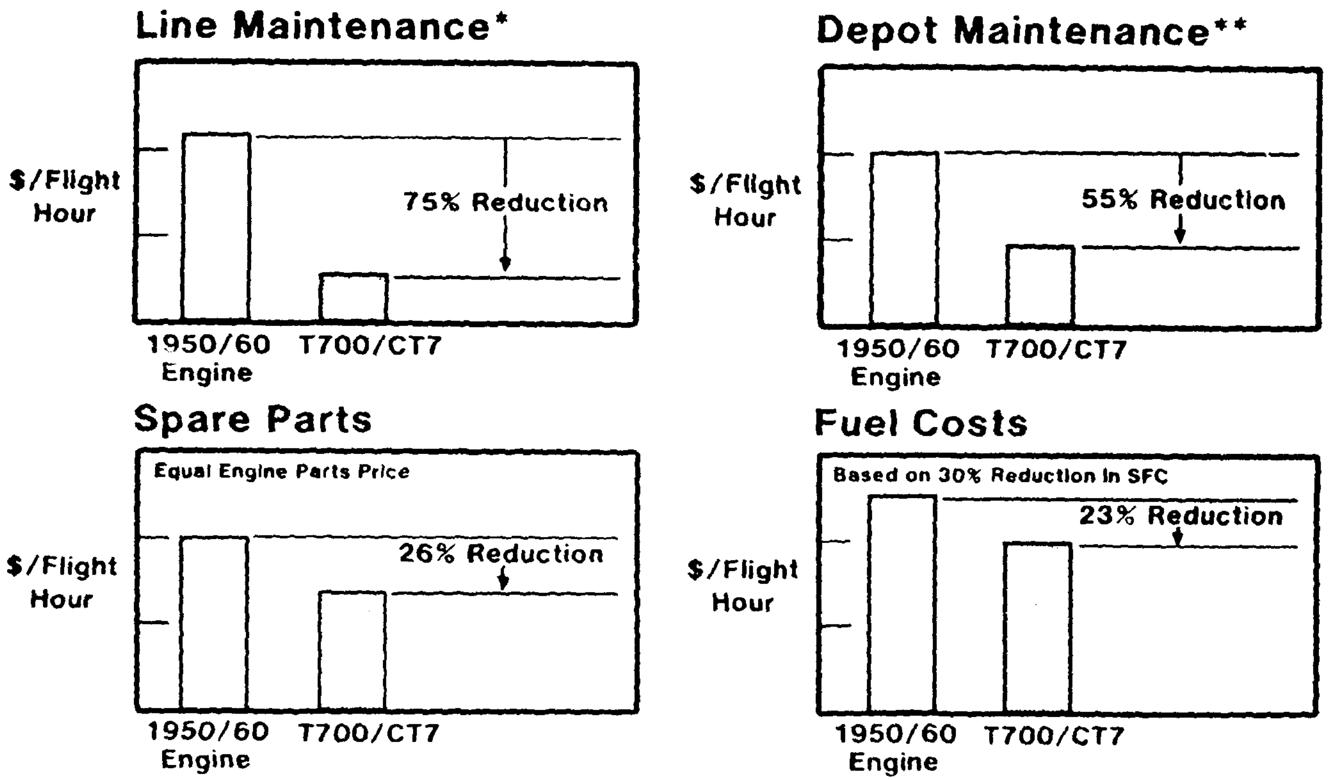
Significant Fuel Savings



100,000 Gallons* Saved Per Engine!

*Based on 5,000 Hours Operation

Lower Life Cycle Cost



* Per MICV-UTTAS Article From Army, July 1973

**Per AFM 173-10, 1 April 1973

T700-402(030582)

Field Experience Summary

- T700 Established Record at Quarter Million Hours Over Mature Prior Generation Engines — Big LCC Impact
  - Six-Fold SVR Improvement
  - Spare Engines 15% Versus 50%, Saves $400 Million
  - Total Line Maintenance Required Since 1978 — Less Than One Man-Year

PROGRAM ELEMENTS

PROGRAM ELEMENTS

Many factors contributed to the results of the T700 engine program. The key development factors have been divided into five groups. This grouping assisted in the study analyses; however, these elements are not independent of each other and in fact have large overlaps. The more significant of these overlaps are identified and described in the pages that follow.

PROGRAM ELEMENTS

- CONTRACT
- MANAGEMENT
- DESIGN
- MANUFACTURING
- TEST AND EVALUATION

CONTRACT

- STRUCTURE
- R&M REQUIREMENTS
- INCENTIVES
- SOURCE SELECTION
- LCC

STRUCTURE

The contracts for the T700 engine addressed reliability and maintainability in the following ways:

a. The instruction for proposal preparation emphasized the part that would be played by the reliability/maintainability program in the supplier slection process.
b. The equipment specification defined R&M requirements, testing, and growth factors.
c. The purchase order contained the life cycle cost structure, and design-to-cost structure.
d. Provisions were made for a warranty incentive agreement.
e. The general management requirements included provisions for corrective action, retrofit, and test failure notification.

HIGHLIGHTS

- CONTRACT INTERFACE SIMPLICITY
- FREEDOM TO EFFECT CHANGES WITHIN SCOPE
- FLEXIBILITY FOR MANAGEMENT DECISIONS

R & M REQUIREMENTS

R&M REQUIREMENTS

The General Electric T700-GE-700 Gas Turbine Engine was developed under Contract #DAAJ01-72-C-0381 (52) with the U.S. Army Aviation Systems Command, dated 15 March 1972. This contract called for the development of the Turbine Aircraft Engine--to be conducted to the Contractor's Prime Item Development Specification (PIDS) AMC-CP-2222-02000, dated 31 December 1971, which had been prepared and submitted to the U.S. Army in response to the U.S. Army's RFQ for the Utility Tactical Transport Aircraft System (UTTAS) in 1971.

Line items in Contract # DAAJ01-22-C-0381 specifically called out that a Reliability Program and a Maintainability Program be conducted in accordance with previously submitted Program Plans which had been reviewed and coordinated with U.S. Army planners well before award of the Development Contract. These items were specified as follows:

Section E

Item No.	Supplies/Services
000104	Reliability Program in accordance with Reliability Program Plans dated 18 January 1972
000105	Maintainability Program in accordance with Maintainability Program Plan dated 10 January 1972

In both the PIDS and in the separate R&M Program Plans, both quantitative and qualitative requirements were specified which were contractual requirements, not goals, and had to be met/demonstrated by the end of the development contract.

The development and evolution of the detail requirements is discussed in the Design portion of this report.

REQUIREMENTS OVERVIEW

- R&M Requirements, both Qualitative and Quantitative, spelled out clearly in PIDS and R&M Program Plans.

- Joint Army/GE Maintainability team formulated requirements based on Viet Nam experience and predicted future requirements.

INCENTIVES

DEVELOPMENT PROGRAM INCENTIVES

The development contract #DAA-JO1-72C-0381(52) dated 15 March 1972, was a Cost Plus Incentive Fee (CPIF) type contract.

Only two (2) items were subject to special incentive/penalty provisions. These were for beating the guaranteed fuel consumption (SFC) and a penalty for late completion of the Preliminary Flight Rating Test (PFRT).

There were no monetary incentives in the T700 contract for meeting R&M contractual requirements. Due to the emphasis which had been placed on R&M from the very outset of the Advanced Technology Engine (ATE) GE12 Demonstrator Program and in the ensuing RFQ, there was little need for monetary type incentives.

DEVELOPMENT PROGRAM INCENTIVES OVERVIEW

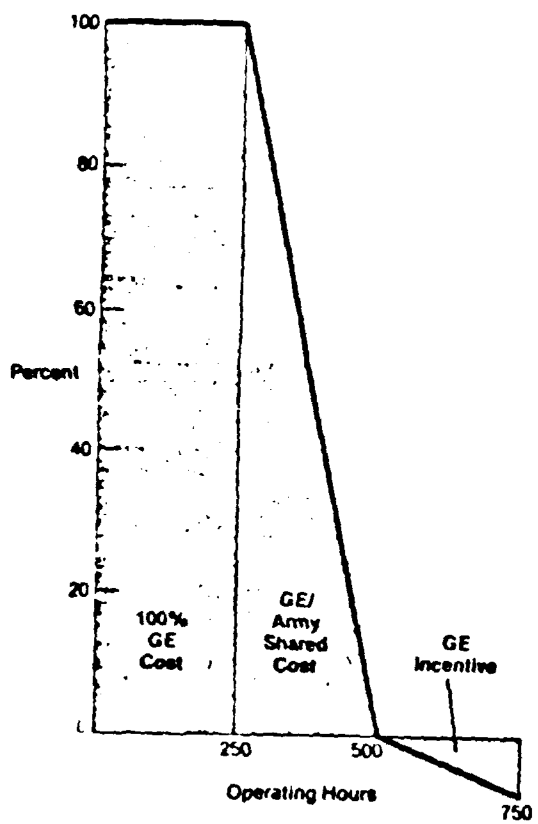
- CPIF CONTRACT
- NO INCENTIVE FEES FOR R&M
- R&M GIVEN EQUAL PRIORITY WITH ALL OTHER CHARACTERISTICS
- EMPHASIS BY BOTH ARMY AND CONTRACTOR MANAGEMENTS ON IMPORTANCE OF R&M REQUIREMENTS

RELIABILITY IMPROVEMENT PROGRAM INCENTIVES

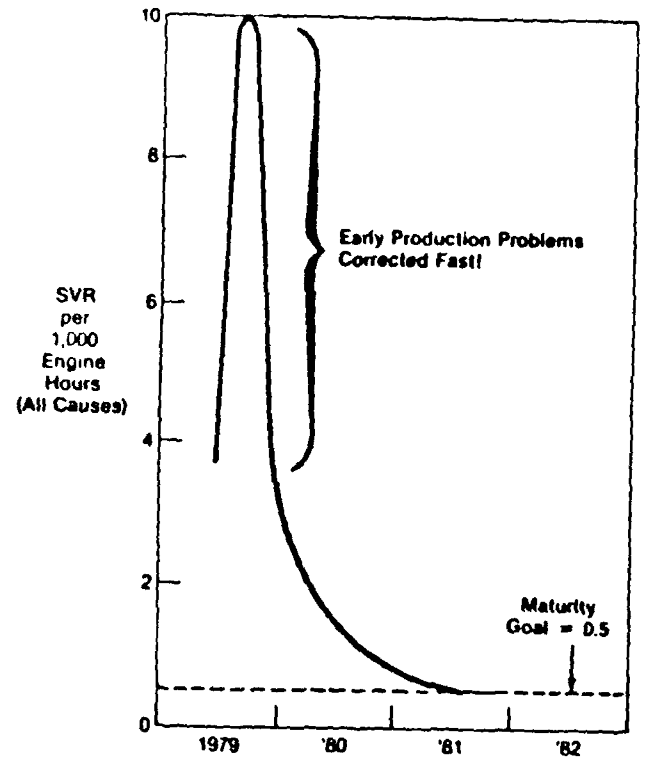
During the first three years of production, General Electric produced the T700 under a warranty incentive agreement. The warranty agreement broke down into three segments. GE had to absorb 100 percent of the cost of repairing engines or components that failed during the first 250 operating hours. GE and the Army shared the repair costs for failures between 250 and 500 operating hours. GE incentives applied only on engines that operated without unscheduled maintenance or repair work beyond 500 hours to 750 hours. It obviously was very much in GE's interest to produce problem-free T700 engines.

The Shop visit rate history for the production T700 was high during the first few months following the introduction of the Black Hawk. Early production or start-up problems developed which had to be corrected. The most significant being the number four bearing support bottoming in the midframe, thereby negating the effect of the bearing support oil film damping feature. Approximately 90 percent of the shop visits in 1979 were removals to correct this discrepancy plus one or two other start-up problems.

T700 Warranty Incentive



T700 Shop Visit Rate



With the warranty during the first three years of production, it was all General Electric's cost burden to correct problems on engines with less than 250 hours. This provided an incentive to move quickly to correct these start-up problems because it was to GE's advantage as well as the U.S. Army's to introduce fixes while the fleet was still small. The latitude existed to do so because at that time in the program GE was under contract to provide total contractor support which meant the contractor had full configuration control and logistics support flexibility.

Although not contractually bound, GE set an internal maturity SVR goal of 0.5 for the T700 for all causes, versus the Army requirement of 0.8 for engine-caused only. The engine reached that goal long before it could be considered a mature field engine.

It is believed the warranty incentive provided a big payoff for the Army because it hastened early solution to start-up production problems and accelerated achieving a mature engine shop visit rate.

Because this approach successfully encouraged the production of problem-free engines, the Army elected to discontinue the warranty after only three years of production.

WARRANTY PROGRAM SUMMARY

- WARRANTY PROGRAM PROVIDED INCENTIVE TO CONTRACTOR TO FIX EARLY FIELD START-UP PROBLEMS WHILE FLEET WAS SMALL
- WARRANTY PROGRAM HASTENED RELIABILITY GROWTH/ LOWER SHOP VISIT RATES
- DUE TO OUTSTANDING T700 ENGINE RELIABILITY RECORD IN FIELD, ARMY ELECTED NOT TO RENEW WARRANTY AFTER FIRST THREE YEARS

SOURCE SELECTION CRITERIA

SOURCE SELECTION CRITERIA

In the cover letter of the Official Request for Quote (RFQ) #DAAJ01-71-Q0455[52] which was issued to General Electric, Pratt and Whitney and Lycoming in July 1971 for the development of a 1500 SHP turbine engine, the following statement is taken from the block entitled, "ITEM(S) TO BE PURCHASED (Brief Description).

"Design, develop, fabricate, test, demonstrate reliability and maintainability and qualify a 1500 SHP, non-regenerative, direct front drive, turboshaft aircraft gas turbine engine for the Utility Tactical Transport Aircraft System (UTTAS)".

The theme of this brief description was carried through the entire RFQ leaving no doubt that the U.S. Army was very serious about R&M being of prime importance to this new engine.

INFORMATION TO QUOTERS

SOLICITATION NO.
DAAJ01-71-Q-0455(52)

ISSUING OFFICE *(Complete mailing address including Zip Code)*

US Army Aviation Systems Command
12th and Spruce Streets, AMSAV-A-PWD
St. Louis, Missouri 63102

ITEM(S) TO BE PURCHASED *(Brief description)*

Design, develop, fabricate, test, demonstrate reliability and maintainability and qualify a 1500 HP, Non-Regenerative, Direct Front Drive, Turboshaft Aircraft Gas Turbine Engine for the Utility Tactical Transport Aircraft System (UTTAS).

THIS PROCUREMENT IS:

X	UNRESTRICTED
	SET-ASIDE. (THIS IS A % SET ASIDE FOR ☐ SMALL BUSINESS OR ☐ LABOR SURPLUS AREA CONCERNS.) (SEE SECTION C OF TABLE OF CONTENTS IN THIS SOLICITATION FOR DETAILS OF THE SET-ASIDE.)
	OTHERWISE RESTRICTED TO

Under Section D of the RFQ the Evaluation Factors were defined for making the award of a contract as a result of this RFQ.

In paragraph D.5, three major evaluation elements were delineated with the possible points to be awarded for each of these elements as follows:

EVALUATION ITEM	POSSIBLE POINTS
Technical	700
Management	150
Cost	150

Under sub-paragraph D5.1 Technical, sub-paragraph D5.1.1 breaks down the elements for the evaluation of the design and performance of the engineering and logistical critical components. This statement points out that specific attention would be given to the following items:

1) Systems Design
2) Component Design
3) Trade-Off Analysis

Items of the System Design will include:

1) Sub-system Development.
2) Configuration/Weight Analysis.
3) Performance/Power Extraction.
4) Operating Limitation.
5) Reliability and Maintainability.
6) Systems Integration.
7) Materials.
8) Vulnerability and Serviceability.
9) Producibility/Production Margins.
10) Condition Monitoring.
11) Diagnostics.

It may be noted from this set of evaluation criteria, that Reliability and Maintainability were given careful consideration with other engine characteristics such as performance and weight.

There has never been any question from the very beginning of this program that Reliability and Maintainability were given very high priority in the selection of this new Army helicopter engine.

SOURCE SELECTION CRITERIA OVERVIEW

- U.S. ARMY CONSISTENT THROUGHOUT RFQ ON EMPHASIS AND HIGH PRIORITY FOR R&M.
- R&M GIVEN EQUAL PRIORITY ON EVALUATION CRITERIA WITH OTHER ENGINE CHARACTERISTICS FOR SOURCE SELECTION AS PERCEIVED BY THE CONTRACTOR.
- NO DOUBT THAT U.S. ARMY WAS SERIOUS ABOUT R&M REQUIREMENTS FOR THIS NEW HELICOPTER ENGINE.

LCC CONSIDERATIONS

LCC CONSIDERATIONS

From the very outset of the T700 program, Life Cycle Cost was a driving factor in the design of the engine. A prime example of this was the charges made in the engine design between the ATE (GE12) Phase and the design proposed in response to the Army's RFQ in 1971.

In May, 1971, several maintenance tasks were timed on the ATE (GE12) Demonstrator engine to determine Remove and Replace Times. For example, it required 111.3 man-minutes (mm) to remove and replace (R/R) the fuel control, and 434 mm plus numerous hand tools and several special tools to R/R the combustion liner. The contract GE later signed guaranteed R/R of 29 and 143 mm, respectively, with no special tools. Actual demonstrated times with Army mechanics in June 1976 were 8 mm and 96 mm, respectively, with no special tools.

The ATE Maintainability demonstration was valuable for many reasons, and one of the most important was the verification of analysis techniques. A task analysis methodology, including a set of standards, had been developed on other General Electric engine programs and, prior to the ATE demonstration, was applied to the GE12 drawings to determine expected task times. The actual demonstration effort along with the practice sessions were utilized to tune the standards so that, as a result, there was a known confidence level in the Maintainability task analysis process.

Following the ATE program, the GE12 was completely redesigned to address the identified qualitative and quantitative problems. This redesign effort involved several iterations, maintained the integrity of the gas path, created a 4-module engine, put the accessory module on top for better access, and eliminated the need for any special tools at any field level. The resulting design was proposed for UTTAS and designated the T700-GE-700 engine. The design greatly simplified the external configuration by increased internal porting in frames and castings and addressed every problem/concern identified by the ATE "M" demonstration team.

LCC CONSIDERATIONS OVERVIEW

- LIFE CYCLE COST A DRIVING FACTOR FROM VERY BEGINNING IN DESIGN OF THE T700 ENGINE.
- EARLY MAINTAINABILITY DEMONSTRATION OF ATE (GE12) DEMONSTRATOR POINTED UP SEVERAL AREAS WHERE IMPROVEMENTS WERE REQUIRED.
- SIGNIFICANT NUMBER OF CHANGES MADE TO THE DESIGN OF THE T700 TO CORRECT R&M DEFICIENCIES FOUND ON THE ATE (GE12) DEMONSTRATOR.

The proposed design was accepted and the contract was awarded to General Electric in March 1972.

LIFE CYCLE COST

Life cycle costs represent the accumulation of all costs of a system over the entire span of its existence. Included are the following elements:

- Development. These costs cover the 11-year period described earlier.
- Acquisition. Production is expected to extend over a decade for the T700.
- Ownership. This phase extends from the time of the first delivery until the last system is retired from the Military--more than 25 years!

With the operational phase accounting for 80% of the life cycle cost, the driving forces of the basic system design are features which will have a great impact on life cycle cost. This was the prime focus of the initial design and development phase.

LIFE CYCLE COST

- LCC REPRESENTS ACCUMULATION OF ALL COSTS OF A SYSTEM OVER ENTIRE SPAN OF ITS EXISTENCE.
- INCLUDES DEVELOPMENT, ACQUISITION AND OWNERSHIP.
- OPERATIONAL PHASE ACCOUNTS FOR OVER 80% OF LCC.
- R&M HAS BIG IMPACT/PAY-OFF DURING THIS PHASE AND THUS HAS BIG IMPACT ON OVERALL LCC.

OPERATING AND SUPPORT COSTS

Representative ownership costs which are the driving factors in the operational cost of a weapons system are:

- o Unscheduled On-Line Maintenance
- o Depot Maintenance
- o Spare Parts
- o Fuel Cost

These are important because ownership costs are about 80% of the systems life cycle cost. The T700 engine provides significant reductions in all four areas when compared to 1960 vintage engines. For example: Unscheduled line maintenance is reduced by 75%. Scheduled depot maintenance has been totally eliminated by the "on condition" maintenance concept. Reduced maintenance requirements make significant reductions in spare parts possible, and the cost of these parts has been further controlled by "Design-to-cost." Fuel cost reductions were possible because of the extremely low part-power fuel consumption characteristics of the T700.

Specific fuel consumption characteristics dictate development and production cost to a large degree and low fuel consumption is extremely important for large commercial aircraft because this cost represents a very large portion of total cost. However, despite today's inflated oil costs, fuel is a relatively small portion of the true total life cycle cost of a military system.

OPERATING AND SUPPORT COSTS OVERVIEW

- T700 ON-LINE MAINTENANCE REDUCED BY 75%.
- DEPOT MAINTENANCE SIGNIFICANTLY REDUCED BY ELIMINATION OF SCHEDULED INSPECTIONS/OVERHAULS.
- REDUCED MAINTENANCE RESULTED IN FEWER SPARE PARTS.
- FUEL CONSUMPTION/COSTS REDUCED BY 25-30%.

Parts Cost is the next largest piece of the Acquisition Cost. Here reliability/durability is probably the key. To illustrate, let us assume a combustor needed replacement every 700-900 hours. If 6000 hours life could be obtained at a somewhat higher parts cost, the more expensive, longer lasting part could be cheaper on a life cycle cost basis.

Although higher parts cost may reduce life cycle cost, there is a balance required between acquisition cost and a life/durability factor.

Vietnam experience showed that higher acquisition cost, which provided longer life in the combat theater, proved less costly to the Military.

- Direct Labor. Significant development effort was turned toward reducing the cost of repairs -- reducing labor cost. Reduced man-hours result from lowered task times, and thus fewer persons required. This frees up limited manpower for other military purposes.
- Support Cost. The indirect costs are cost of the cook, bottlewasher, the truck driver, the mailman, and everything which is indirectly related to manpower in a direct labor function. As direct labor is reduced, the requirement for other support elements is also reduced.

The balance between acquisition cost and life/durability/reliability is made during the initial design, development and RFQ phases. For the remainder of this discussion, it is assumed the basic design has been committed.

ACQUISITION LCC COSTS

- HIGH RELIABILITY DESIGN OF T700 COMBUSTOR WITH HIGHER PROCUREMENT COST PRODUCED LOWER L.C.C. THAN LOWER COST/SHORT LIFE DESIGNS OF THE 60'S.
- IMPROVED MAINTAINABILITY RESULTED IN REDUCED DIRECT LABOR HOURS.
- INDIRECT SUPPORT REDUCED AS DIRECT LABOR REDUCED.
- BALANCE BETWEEN ACQUISITION COST AND LIFE/DURABILITY/RELIABILITY WAS MADE DURING INITIAL DESIGN, DEVELOPMENT AND RFQ PHASES.

DESIGN-TO-COST

Design-to-Cost became a DoD policy in 1974, after the UTTAS engine competition and after the engine contract was written. Because a large number of helicopters and engines were to be procured, General Electric and the Army agreed to add a signficant DTC incentive clause to the T700 contract. This occurred near the end of the first year of effort. Thus, it is believed the T700 engine is the first engine to have been designed, developed, qualified and released for production utilizing DTC principles.

The philosophies of DTC have been applied at GE's aircraft engine business since 1971. Long before DTC was added as a T700 contract clause, GE had been applying the principles in its own self interest. GE felt it mandatory to achieve the completion of development within the cost guide lines established by the Army and thus initiated extremely rigid controls. GE instituted this major cost control program on its own because two-thirds of the cost of T700 development were associated with hardware.

Design Trade-offs

Designers performed a number of trade-offs as each part went through preliminary and final design phases. Among the considerations were RFQ specification requirements, reliability objectives and maintainability requirements as well as a number of industry standard practices.

Other considerations included asking whether the part could be manufactured with an adequate quality control plan. And, finally, overall manufacturability was determined. GE's approach utilized a team of engineer, designer, industrial engineer and a quality control engineer to determine if all requirements were achieved. A number of "Iterative" designs were required.

DESIGN-TO-COST

- o DoD POLICY ISSUED -- MAY '74
- o ADDED REQUIREMENT TO T700 LATE '73
  - STRONG DRIVE BEHIND DTC
  - HIGH VOLUME OF UTTAS PRODUCTION.

DESIGN TRADE OFFS

- COST
- SPEC. REQUIREMENT (RELIABILITY)
- MAINTAINABILITY
- WEIGHT CONTROL
- INDUSTRY STANDARD
- QUALITY CONTROL
- MANUFACTURABILITY

PART "DESIGN"

Before this process was initiated, the engine was divided into a number of "value subassemblies." Each subassembly was given a value sub-division so that before the detail design began, cost goals or "bogeys" were established. In turn, the Bogeys added up to a percent of the objective DTC value.

There are more than 3000 parts in the T700 engine, of which 700 are prime components or assemblies. Initially, items were classified in two categories--those costing more-than-$500 and those costing less-than-$500.

The design effort had just been started when it was found that about 15 individual parts constituted over 60% of the total cost of the engine. Each of these cost over $2000 and comprised only about 2% of the parts count.

Addressing the problem of these high value parts, all items were reclassified into three categories. The highest value parts received concentrated attention.

Next, parts were identified which affected life cycle cost to the greatest extent. A good example is the combustion liner. (The least expensive part may not necessarily be the lowest cost for the overall life cycle cost.) The requirement established by the Army was very clear. The base line combustor design had a life objective of 5000 hours. (Very few gas turbine engines have combustors which last 5000 hours.) The T58 combustor is representative of the first generation gas turbine helicopter engine part. It is a very low-cost pierced sheet-metal fabrication and requires inspection at relatively short intervals to ensure continued safe operation.

DESIGN TO COST PROCESS

- T700 DIVIDED INTO A NUMBER OF "VALUE SUB-ASSEMBLIES".
- COST GOALS OR BOGEYS ESTABLISHED FOR EACH "VALUE SUB-ASSEMBLY."
- 15 INDIVIDUAL PARTS IN T700 ENGINE CONSTITUTED OVER 60% OF TOTAL COST.
- HIGH VALUE PARTS CLASSIFIED INTO THREE CATEGORIES.
- HIGHEST VALUE PARTS RECEIVED CONCENTRATED ATTENTION.
- PARTS IDENTIFIED HAVING GREATEST IMPACT OF LCC:
  - COMBUSTOR PRIME EXAMPLE.
  - HIGHER INITIAL PROCUREMENT COST RESULTS IN LOWER LCC.

Until one recognizes the engine must be partially disassembled and usually removed from the helicopter to accomplish that disassembly, one would not imagine that a part change would be expensive. In this case, low first cost is by no means low life cycle cost.

The T700 machined ring combustor was designed to operate 5000 hours without repair. It provided a decrease in maintenance cost and approximately 5 to 1 lower support cost. It was therefore more cost effective to spend more money for the longer life part to achieve the lower life cycle cost benefits. This example is typical of many examples throughout the engine where the initial design was affected by the life cycle cost considerations. This realization influenced the cost bogeys established and the design to achieve the 5000-hour objectives.

DESIGN TO COST SUMMARY

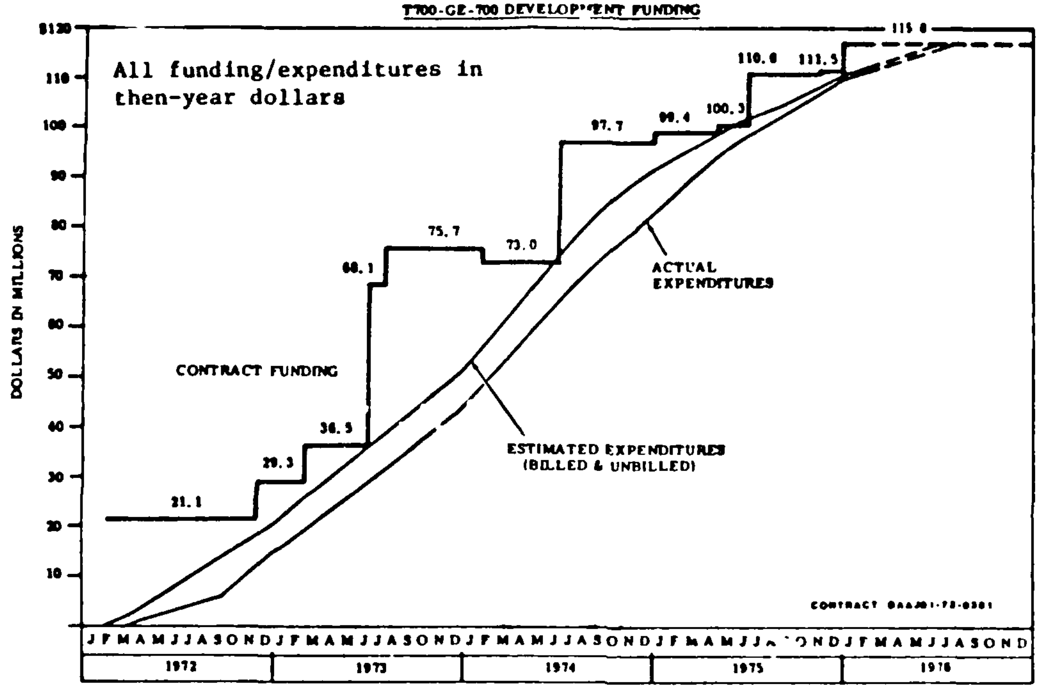
- R&M FACTORS WEIGHTED HEAVILY IN LIFE CYCLE COST STUDIES.
- DESIGN TO COST APPLIED THROUGHOUT T700 DESIGN/DEVELOPMENT PROGRAM.
- MANY TIMES HIGHER INITIAL ACQUISITION COSTS RESULTING IN LOWER LIFE CYCLE COSTS, PROVED TO BE COST EFFECTIVE, I.E., T700 COMBUSTOR.
- EFFECTIVE EMPLOYMENT OF DESIGN TRADE-OFFS IMPORTANT TO OBTAIN LOWEST LIFE CYCLE COSTS.

DEVELOPMENT PROGRAM FUNDING

T700 DEVELOPMENT PROGRAM FUNDING

The T700 full scale development program included: engine development through PFRT and MQT; XT and YT engine procurement for the UTTAS and AAH field programs; spare engine parts technical representative coverage for over 10,000 field operating hours; and other air vehicle support. This program was funded under contract DAAJ01-72-0381. Page IIA-41 shows the actual and estimated (billed and unbilled) expenditures compared to the incremental funding received for the development program for the period February 1972 to March 1976. Page IIA-41 also provides a summary of the major Government funding received for the overall program. The actual program cost was less than 8 percent over target cost during the high inflation rate periods of 1973, 1974 and 1975.

T700-GE-700 DEVELOPMENT FUNDING



MAJOR U.S. GOVERNMENT FUNDING

			$ Millions
DEVELOPMENT			
o GE12 DEMONSTRATOR PROGRAM		8.6	124.4
o T700-GE-700 DEVELOPMENT PROGRAM		115.8	
- MQT Program	59.4		
- UTTAS Vehicle Support	35.1		
- AAH Vehicle Support	21.3		

MANAGEMENT

MANAGEMENT

Management is the second of the five areas identified as important to producing high quality military equipment. The three major facets of management shown are discussed in the pages following.

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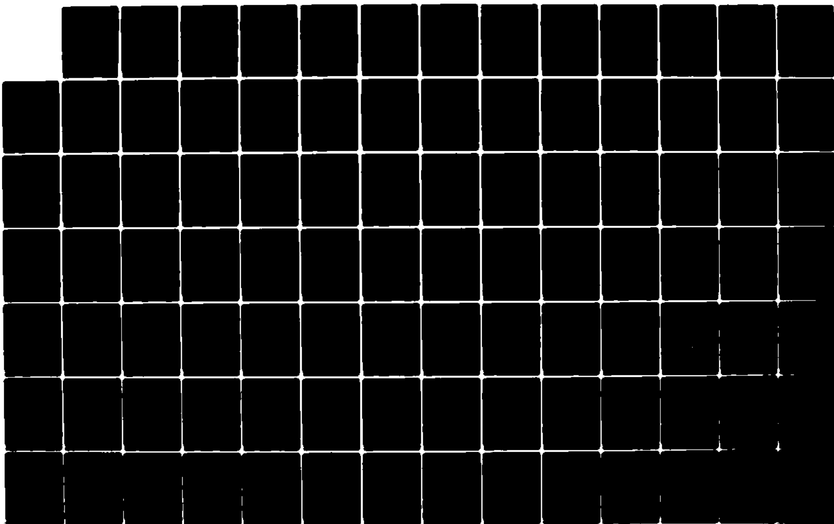
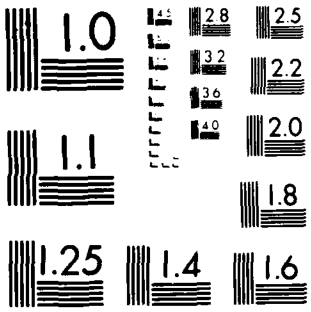




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

MANAGEMENT

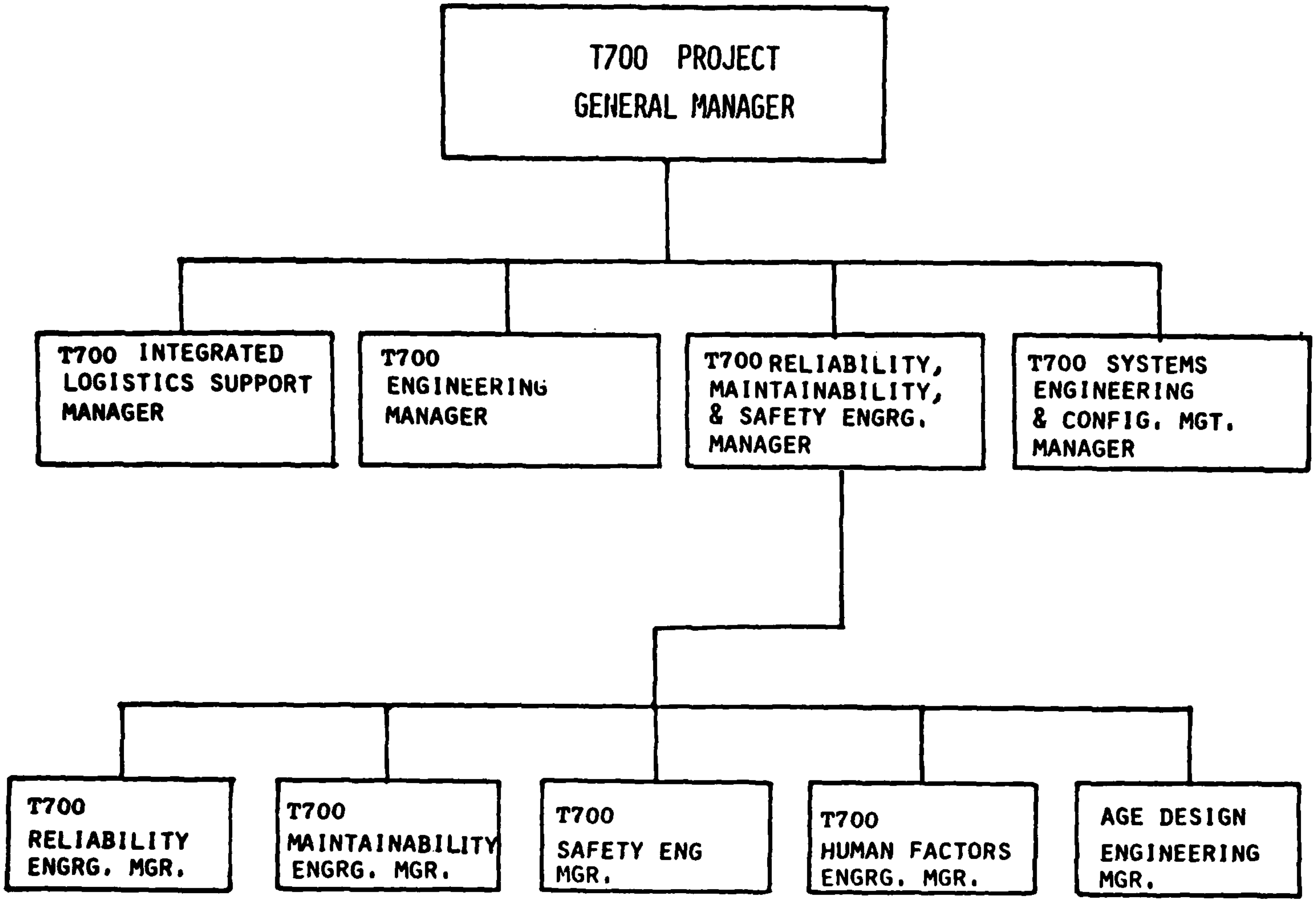
- ORGANIZATION
- CONTROL & EMPHASIS
- SUBCONTRACTORS/SUPPLIERS

ORGANIZATION

From the very outset of this program starting with the RFQ in 1971, high level emphasis was placed on the management and control of both R&M. Attachments M5 and M6 to the RFQ outlined explicitly the detailed contractual requirements for Reliability and Maintainability planning, control and demonstration. The RFQ specified very clearly that Reliability, Maintainability, Safety and Human Factors Engineering all be coordinated/integrated efforts and the Manager of these "ilities" report to the Project General Manager on the same level with Design Manager and Integrated Logistics Support Manager.

As may be noted in the T700 Organiz tional Chart each of the "ilities" was an independent sub-section with each of these managers reporting to a single section-level manager who reported to the T700 Project General Manager.

This organizational structure provided for each of the "ilities" to interface/coordinate their efforts. By having the Manager of Reliability, Maintainability and Safety Engineering reporting to the Project General Manager, equal priority for the "ilities" along with the Design and ILS functions was emphasized.



RELIABILITY AND MAINTAINABILITY ENGINEERING ORGANIZATION

PLANNING, CONTROL & EMPHASIS

PLANNING, CONTROL AND EMPHASIS

The following discussion on the Planning, Control and Emphasis is broken down into separate discussions on Reliability and Maintainability.

Reliability

The lessons learned in Southeast Asia with U.S. Army helicopters were loud and clear. A large improvement had to be made in the basic reliability of engines for the next generation of U.S. Army helicopters. The need for scheduled hot section inspections had to be eliminated and scheduled overhauls had to be replaced by 'on-condition' maintenance. Engine components had to be designed with margin to cope with a wide range of environmental conditions and still survive.

In writing the RFQ for the 1500 SHP Turbine Engine for the UTTAS Program, Army planners factored in these requirements in Attachment M5 of the RFQ in great detail.

This section of the RFQ also delineated how the Reliability Program Plan should be prepared by the Contractor and required a detail management control system/schedule to be defined showing the key milestones on how the Contractor planned to meet the specific Contractual Reliability requirements.

The prime management controls employed during this development program to assure that the Reliability requirements were being met in a systematic manner included:

- Overall Program Progress Reviews (PPR's) - (4)
- Monthly Reliability Progress Reports
- Quarterly Design/Functional/Operational Analysis Reports
- Quarterly Reliability Prediction Reports
- Quarterly Malfunction Summary Reports
- Quarterly Design Review and Demonstration Summary Reports

Reliability Program Milestones

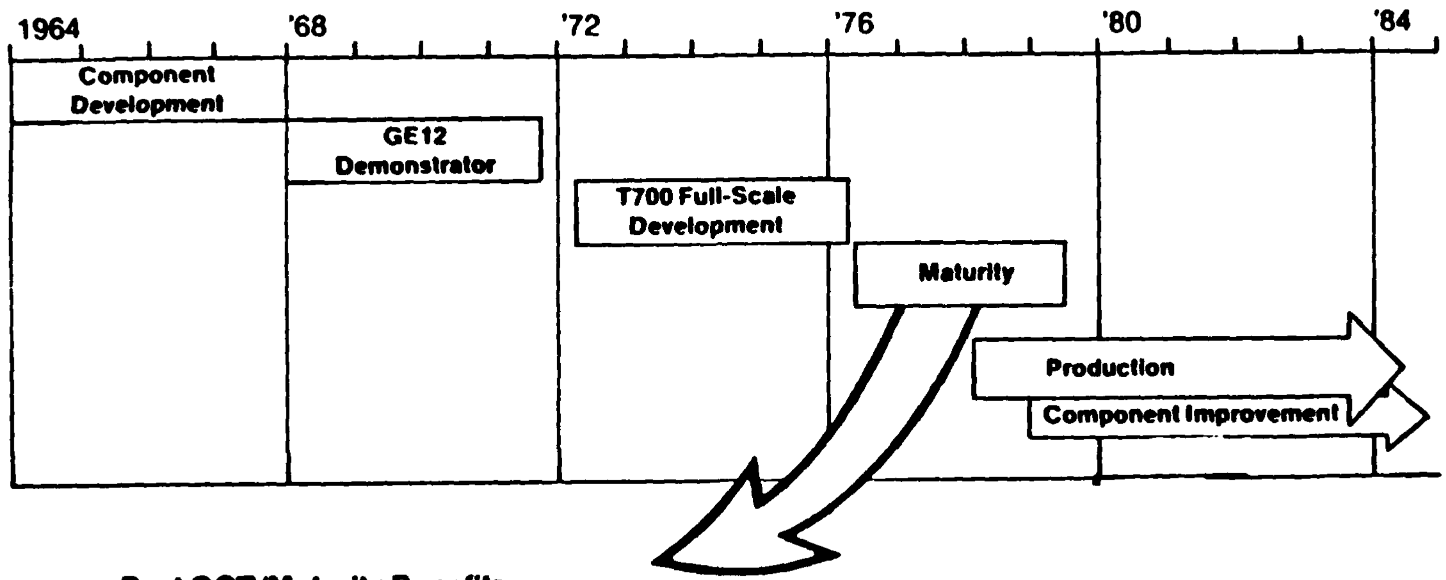
Throughout this program, the UTTAS Program Manager and his staff reviewed Reliability Status at each of the PPR's. Members of the P.M.O's staff, AVLABS, OCRD and AVSCOM participated in numerous design reviews and each component failure/corrective action was reviewed by a member of the P.M.O. staff.

Internally, the Contractor conducted numerous high level design audits and the Chief Engineer's office conducted independent audits of all failures/corrective actions from both factory development and the field.

This series of checks and balances addressed each problem and appropriate corrective action was taken for every problem encountered.

This system of design reviews/problem tracking identified problems during the development program for which fixes could be effected and qualified during the follow-on post-qualification Maturity Program. This resulted in a smoother transition into production with a significant reduction in required design changes during the early years in the field.

T700 Program



Post GCT/Maturity Benefits

- 57 Major Improvements, Production Qualified
- Black Hawk Support System Established
- Smooth Transition to Production

--MAINTAINABILITY

Management

"The Engine Development Maintainability program is intended to exert maximum maintainability influence on engine design during the period of design effort and to protect this inherent maintainability throughout testing." Those were the beginning words in the "M" section of the engine RFO, and some of these requirements are paraphrased below:

- Define method of performing analysis
- Define criteria to design organizations
- Define methods of design control
- Define math models and methods of monitoring status and providing predictions
- Provide equal consideration to maintainability with all design disciplines
- Invest overall responsibility for maintainability at the engine program management level
- Define a multi-level demonstration program which will allow evaluation and problem identification throughout the program
- Maintainability shall be part of all design, mockup, program reviews, and will be randomly audited for effectiveness.

MA AINABILITY MANAGEMENT OVERVIEW

- MAINTAINABILITY GIVEN STRONG EMPHASIS IN RFQ.
- COVERED ALL ASPECTS ON MAINTAINABILITY:
  - ANALYSIS
  - TRANSMITTAL OF DESIGN REQUIREMENTS
  - CONTROL
  - MATH MODEL SIMULATION
  - EQUAL STATUS WITH ALL DESIGN DISCIPLINES
  - DEMONSTRATION PROGRAM

The preceeding is typical of the approach taken by the Army to express their requirements for an engine which has to operate and be maintained in the helicopter environment. There are additional elements, however, that are required for success and management support was judged to be one of the most important.

Army Management Support

Advances in engine technology usually increase complexity. Maintainability in engine design is directly related to simplicity and, thus, it requires considerable design effort to obtain advances in both technology and maintainability.

During the evolution of the Development Concept for UTTAS, it was recognized that this trend to increased complexity had to be reversed. Meeting Maintainability goals had been identified as the primary risk associated with UTTAS development. Further, it was stated that "it is a risk area not because the goals are not technically achievable but because the technical community will have to change from its traditional orientation on performance to this goal." That statement alone indicates the depth of understanding that existed in the crucial planning stages of UTTAS. The planners also understood that requirements and priorities must be stipulated and supported consistently in order to achieve the stated Maintainability goals.

MAINTAINABILITY EMPHASIS

- U.S. ARMY PLANNERS RECOGNIZED NEED TO REVERSE TREND TOWARD INCREASING COMPLEXITY.
- U.S. ARMY PLANNERS RECOGNIZED NEED TO CHANGE THE 'TECHNICAL COMMUNITY'S' ATTITUDE TOWARD MAINTAINABILITY AND GIVE IT EQUAL PRIORITY WITH OTHER PARAMETERS SUCH AS WEIGHT AND PERFORMANCE.
- THIS ATTITUDE WAS CHANGES ON THE T700 PROGRAM AND ARMY MANAGEMENT CONSISTENTLY APPLIED EQUAL EMPHASIS TO MAINTAINABILITY THROUGHOUT THE DEVELOPMENT PROGRAM.

Prior practice was that users would verbalize easily and frequently about Maintainability; however, all the RFQ and Contract specific requirements were identified for performance, weight, cost, test program, and schedule with little mention of "M" except perhaps Maintenance Index (MI) at the system level.

This was changed during the T700 Engine Development Program. The requirements were well stated, and the priorities were applied consistently from the Project Manager down through the component engineers.

MAINTAINABILITY PROGRAM PLAN

A very detailed Maintainability Program Plan was prepared in accordance with Attachment M6 of the RFQ. This document then became a line item #000105 of the final contract.

This Program Plan (Reference Page IIB-19) spelled out in detail all of the methodology and procedures to be executed by the Contractor in regard to planning and controlling the Maintainability activities during the engine development program.

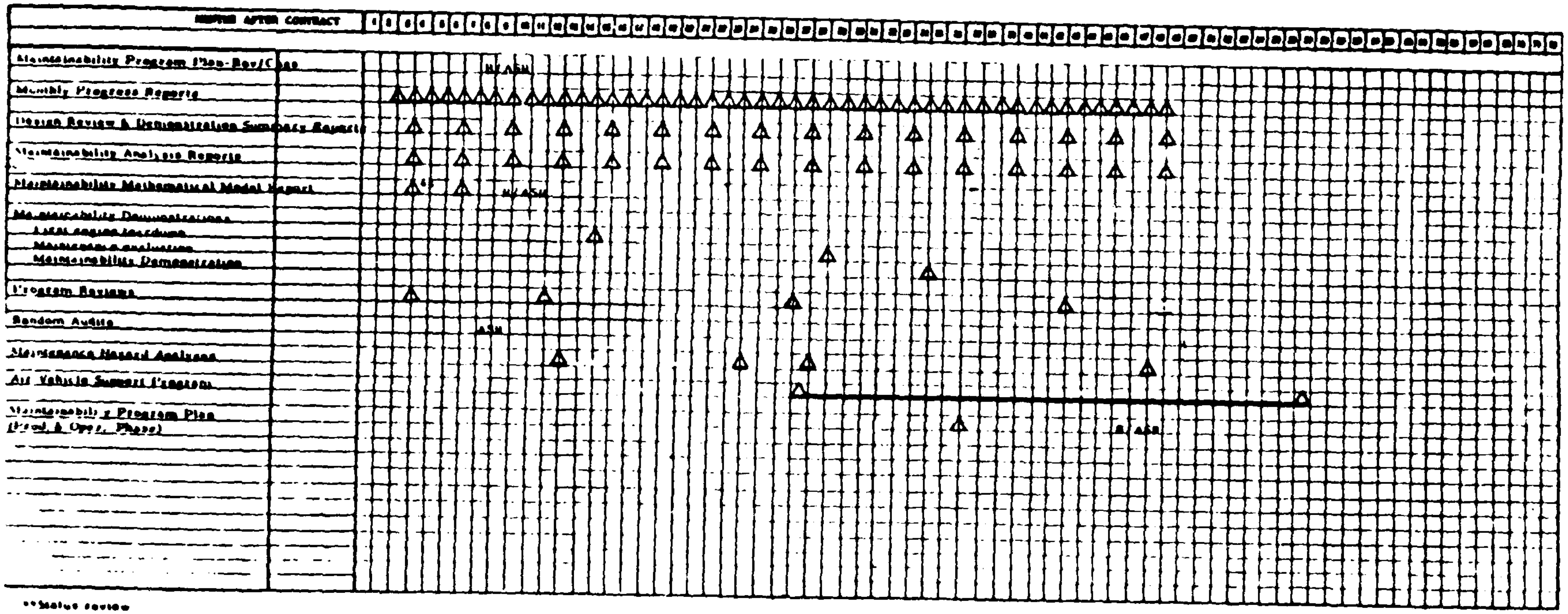
The prime vehicles for management control/measurement included:

- Monthly Progress Reports
- Quarterly Design Review and Demonstration Summary Reports
- Quarterly Maintainability Analysis Reports
- Maintainability Demonstrations (3)
- Overall Program Review (PPR's) (4)
- Random Audits (Unscheduled)
- Maintenance Hazard Analysis (4)

During the overall Program Progress Reviews (PPR's), the UTTAS PMO and his staff would review the total engine program status including Maintainability.

During the Official Maintenance Demonstration which was conducted by Army mechanics from Ft. Eustis, VA., the UTTAS PMO was in attendance as was the T700 Project General Manager.

Each of the milestones in the Maintainability Plan was tracked and was treated on an equal basis with all other contractual milestones. There were no financial penalties or incentives attached to these milestones; however, this did not appear to degraded the compliance and priorities placed by upper level management on assuring these milestones were met on schedule.



Maintainability Program Plan

PLANNING AND CONTROL R&M EMPHASIS

- HEAVY EMPHASIS IN RFQ FOR BOTH R&M.
- RFQ SPECIFIED FORMAT FOR R&M PROGRAM PLANS.
- ORGANIZATION PUT INTO PLACE TO GIVE EQUAL PRIORITIES TO R&M, DESIGN AND ILS.
- UTTAS PMO AND T700 PROJECT GENERAL MANAGER BOTH PARTICIPATED IN R&M PROGRAM REVIEWS AND MAINTAINABILITY DEMONSTRATION.
- HIGH LEVEL DESIGN REVIEWS/AUDITS CONDUCTED BY GE CHIEF ENGINEER'S OFFICE.
- HIGH LEVEL ARMY PARTICIPATION IN ALL PHASES OF R&M PROGRAM.

MONITOR / CONTROL of SUBCONTRACTORS & SUPPLIERS

Once vendors were chosen, the respective R&M Manager for the prime engine contractor set up scheduled Design Reviews with the vendors and a reporting system was also established for Quarterly Progress Reports as well as a system for reporting all failures/corrective actions during the component development program.

Progress/status reports on each critical component were presented by the respective Design Manager and R&M manager at each Program Progress Review (PPR) which was attended by the UTTAS PMO and his staff.

All critical T700 subcontracted components were given the same emphasis in terms of R&M as the basic engine by both U.S. Army and GE management.

SUBCONTRACTOR & SUPPLIER R&M CONSIDERATIONS

- RFQ FOR UTTAS ENGINE EXPLICIT IN DEFINING PRIME VENDOR'S RESPONSIBILITY FOR ASSURING SUBCONTRACTOR'S MET ALL R&M REQUIREMENTS.
- SPECIFIC R&M SPECIFICATIONS WERE INCLUDED IN ALL RFP'S TO ALL COMPETING VENDORS.
- VENDOR R&M PLANS GIVEN HEAVY WEIGHTING IN FINAL SELECTION PROCESS.

SUBCONTRACTOR R&M REQUIREMENTS OVERVIEW

- R&M REQUIREMENTS FOR SUBCONTRACTORS CLEARLY STATED IN RFQ.
- R&M REQUIREMENTS SPELLED OUT IN DETAIL IN T700 R&M PROGRAM PLANS WHICH WERE PART OF THE T700 DEVELOPMENT CONTRACT
- BOTH ARMY AND GE MANAGEMENT PUT HEAVY EMPHASIS ON VENDOR COMPLIANCE TO R&M REQUIREMENTS.
- R&M REQUIREMENTS ON VENDORS AND SUBCONTRACTORS GIVEN SAME EMPHASIS AS ON BASIC T700 ENGINE.

DESIGN

DESIGN FACTORS

System design is the fundamental element in achieving a supportable system. Key factors in the system design are listed on the facing page and described in subsequent charts.

DESIGN FACTORS

- REQUIREMENTS
- ALTERNATIVE STUDIES
- DESIGN ANALYSES
- PARTS AND MATERIAL SELECTION AND CONTROL
- DERATING CRITERIA
- THERMAL AND PACKAGING CRITERIA
- ST/BIT MECHANIZATION AND GROWTH
- FEATURES TO FACILITATE MAINTENANCE

DEVELOPMENT of DESIGN REQUIREMENTS

DEVELOPMENT OF DESIGN REQUIREMENTS

The important difference from predecessor engine models and the T700 was the evolution of stringent but practical reliability and maintainability requirements and their achievement during the design and development program.

Historically, aircraft engines had been developed as a result of a need for an advancement in "state-of-the-art" parameters, such as performance, weight, and acquisition cost. In the past, R&M, as design parameters, had often been neglected except for attempts at rearranging external configuration to meet specific needs. Most basic maintenance problems were resolved by the addition of "special tools" and increased detail in the technical publications and basic reliability problems were solved by "beefing up" or "Band Aid" fixes and massive retrofit programs after the engine was in production. This was not the case with the T700 engine program. The evolution and design of this engine reliability and maintainability are traced from the demonstrator program through the official Model Qualification Test (MQT) Demonstration and show a consistent high priority approach for R&M from Government and Industry Project Managers.

Basic requirements were evolved from previous user experience as summarized in the next page.

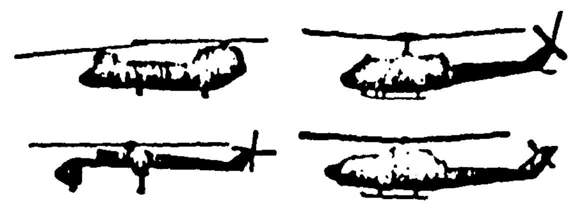
Late 1960s Engine Experience

Reliability Characteristics

- 600-1,200 Hour TBO Due to Compressor and Turbine
- 600-900 Hour Hot Section Maintenance Interval (Combustor)
- High Shop Visit Rate to Intermediate and Depot
  - 0.5 Mechanical Failure
  - 0.4 FOD
  - 0.3 Improper Maintenance
  - 0.2 Scheduled (TBO)
  - 0.2 Seal Leakage
  - 0.1 Erosion
  - 1.3 Other (Airframe, Convenience Operator, Unknown)

  3.0 Total SVR

Ref: USAAMRDL TR 73-28



Maintainability Characteristics

- Complicated Rigging of Fuel Control
- High Maintenance Induced Failure Rate
- Accessibility Often Difficult
- Time Consuming Safety Wiring
- High MMH Burden for Hot Section Replacement

MAINTAINABILITY REQUIREMENTS

Most experienced maintenance technicians can explain, in detail, the maintainability problems with their current powerplants. The management problem has always been to (1) document this collective experience and express the compilation in quantitative and qualitative terms as a timely design requirement, and (2) devise design methods to comply with these requirements.

U.S. Army Concept Formulation studies for replacement of the UH-1 transport helicopter began in the mid sixties and resulted in a system called UTTAS (Utility Tactical Transport Aircraft System). This system *had some challenging* requirements, such as lifting a crew of three plus eleven combat-equipped troops out of ground effect at a 4,000 ft. altitude on a 95°F day, when combined with:

- 37% - 50% reduced maintenance man hours
- 20% - 30% reduced fuel consumption/engine
- Improved survivability
- 11,500 shaft horsepower
- Integral engine protection against sand and dust
- Reduced logistics support

The Army sponsored a four-year Advanced Technology Engine (ATE) demonstration program with General Electric which substantiated that the performance requirements were achievable in a full-scale development program. This ATE demonstrator was identified as the GE12. During the later period of the ATE demonstrator program, Army and GE R&M engineers conducted an in-depth review of then-current Army engine experience and made postulations about the future operational and maintenance environment. A joint R&M evaluation of the GE12 engine was also conducted and problem/concern areas identified.

Army planners stated that the "reduction in maintenance and logistics support requirements was the major technical goal for the UTTAS" and identified the primary risk associated with UTTAS development as meeting Maintainability Goals.

As a result of this intense emphasis from Army management, many meetings and discussions were held between GE and Army to determine types and methods of defining Maintainability requirements and monitoring status. The results were incorporated in the engine Request For Quotation (RFQ), contract, and full-scale development of the T700 engine.

Specific Contract Requirements

Army Maintainability engineers, with extensive backgrounds in the aircraft industry, prepared the qualitative and quantitative Maintainability ("M") requirements and objectives for UTTAS engine development. This list became a part of the "Prime Item Development Specification" (PIDS), which was the primary design specification for engine development. These "M" requirements represented the best ideas collected from experienced specialists in Industry and the Military.

The following is representative of those Maintainability Requirements/Objectives which were the most significant drivers of the T700 design.

REQUIREMENTS/OBJECTIVES

QUALITATIVE

- COMMON HAND TOOLS - DESIGN MUST COMPLY WITH ENGINE REPAIRMAN'S TOOL KIT SC5180-99-CL-A07-MAY 1969.
- SPECIAL TOOLS - MINIMIZE SPECIAL TOOLS FOR ALL LEVELS OF MAINTENANCE.
- CONTROL SYSTEM SHALL BE ACCESSIBLE AND EASILY ADJUSTABLE IN THE FIELD.
- ENGINE SHALL BE DESIGNED FOR EASE OF SERVICING AND MAINTENANCE.
- ENGINE SHALL ALLOW REPLACEMENT OF SHORT MAINTENANCE INTERVAL COMPONENTS WITHOUT REMOVAL OF OTHER COMPONENT PARTS.
- BORESCOPE INSPECTION PROVISIONS SHALL BE MADE IN ALL CRITICAL AREAS WHERE INSPECTION IS NECESSARY.
- THE ENGINE SHALL BE MODULAR.
- THE POTENTIAL FOR MAINTENANCE PERSONNEL ERROR SHALL BE CONSIDERED IN THE DESIGN.
- HUMAN ENGINEERING PRINCIPLES SHALL BE APPLIED TO SIMPLIFY MAINTENANCE PERSONNEL REQUIREMENTS.
- FILTER SYSTEMS WILL HAVE AUTOMATIC EMERGENCY BYPASS WITH SIGNALS TO A WARNING SYSTEM AND MECHANICAL IMPENDING BYPASS INDICATORS.

<u>REQUIREMENTS/OBJECTIVES</u> (CONTINUED)

<u>QUALITATIVE</u> (CONTINUED)

- THE POTENTIAL FOR INADVERTENT DAMAGE BY PERSONNEL SHALL BE CONSIDERED IN THE DESIGN.
- SCREWS OR BOLTS FOR ATTACHMENT OF ANY ONE COMPONENT OR PART SHALL BE ONE SIZE.
- THE ENGINE SHALL NOT REQUIRE MORE THAN ROUTINE PRE-INSTALLATION INSPECTION AFTER 6-8 MONTHS STORAGE IN THE APPROVED CONTAINER.
- THE ENGINE DESIGN SHALL INCORPORATE PROVISIONS FOR WATER WASH COMPRESSOR CLEANING.
- SPECIAL TOOLS - ALL SPECIAL TOOLS, GROUND HANDLING, SUPPORT EQUIPMENT, AND FACILITIES NECESSARY AT DEPOT LEVEL WERE IDENTIFIED WITH THE INITIAL PROPOSAL, AND ANY CHANGES REQUIRED ARMY APPROVAL.

QUANTITATIVE

- CORRECTIVE MAINTENANCE - FIELD LEVELS -- .07 MHR./OP. HR.

- PREVENTIVE MAINTENANCE - FIELD LEVELS -- .03 MHR./OP. HR.

- TOTAL DIRECT MAINTENANCE - ALL LEVELS -- .24 MHR./OP. HR.

- MEAN TIME BETWEEN MAINTENANCE (MTBM) -- 220 ENGINE OPERATING HOURS (EXCLUDING DAILY INSPECTION).

- MEAN DOWN TIME - FIELD LEVELS -- 1.7 HOURS.

- ACTIVE ELAPSED TIME TO REPAIR A CLASS V FAILURE -- 3 HOURS REPAIR OR SERVICING.

- ALL ORGANIZATIONAL REPAIR OR SERVICING MAINTENANCE -- 30 MINUTES.

- ALL ORGANIZATIONAL AND DIRECT SUPPORT MAINTENANCE PROCEDURES SHALL BE CAPABLE OF PERFORMANCE IN ARCTIC CLOTHING AT -54°C WITHOUT DEGRADING THE MEAN ELAPSED TIME BY MORE THAN 50%.

- THE REMOVE/REPLACE, TOTAL AND ELAPSED TIMES AND SPECIAL TOOL REQUIREMENTS WERE PRESENTED IN THE PROPOSAL AND SUBSEQUENT SPECIFICATION FOR: (REF. APPENDIX 50 OF PIDS AS SHOWN ON FOLLOWING PAGES).

  - ALL MODULES (4)
  - ALL REPLACEABLE UNITS (LRU's) (19)
  - POWER TURBINE MODULE COMPONENTS (10)
  - HOT SECTION MODULE COMPONENTS (8)
  - COLD SECTION MODULE COMPONENTS (26)

APPENDIX 50

50. Maximum Removal and Replacement Time. The times tabulated below are the maximum removal and replacement times of engine components by a mechanic with a 95th percentile skill. The line replaceable units (LRU's), modules, and items marked by an asterisk in 50.5 and 50.6 are removed and replaced directly from the engine in the time listed. All other component times listed include the module remove and replace time. Component removal and replacement times do not include time for (a) grinding with associated clearances and assembly/disassembly; and (b) balancing with associated assembly/disassembly. Component removal and replacement times do include time for clearance and runout measurements to assure proper assembly of the components.

	Total Time(2) (man minutes)	Elapsed Time(2) (minutes)
50.1 Modules (3)		
Power Turbine (PTM)	75	38
Hot Section (HSM)	117	63
Cold Section (CSM)	161	86
Accessory (ACC)	44	21
50.2 Line Replaceable Units(1)(3)		
Hydromechanical Control (ACC)	13	13
Wiring Harnesses (CSM)	16	16
Thermocouple Harness (PTM)	13	13
Electrical Control Unit (CSM)	7	7
Primer Nozzles (two) (HSM)	5	5
Torque Sensor (PTM)	5	5
Np Sensor (PTM)	5	5
Igniters (two) (HSM)	8	8
Separator Blower (ACC)	3	3
Fuel Filter Assembly (ACC)	4	4
Anti-icing/Bleed Valve (CSM)	7	7
Radial Drive Shaft (ACC)	3	3
Ignition Exciter (CSM)	6	6
Lube/Scavenge Pump (ACC)	4	4
Alternator Stator (ACC)	4	4
Oil Filter Bypass Sensor (ACC)	4	4
Oil Cooler (ACC)	3	3
Oil Filter (ACC)	2	2
Ignition Lead - Right (CSM)	4	4
Ignition Lead - Left (CSM)	4	4
Engine History Recorder (CSM)	3	3
Fuel Boost Pump (ACC)	3	3
Chip Detector (ACC)	3	3
Sequence Valve (ACC)	8	8

(1) Module assignment shown in parenthesis.

(2) Total Time is total maintenance time with one or two mechanics.
Elapsed Time assumes two mechanics working simultaneously when practical.

(3) Special Tools per Appendix 30.1 and 30.2 are not required for 50.1 Modules and 50.2 Line Replaceable Units.

	Total Time(2) (man minutes)	Elapsed Time(2) (minutes)	Special Tool Ident per Appendix 30.1 & 30.2
30.3 Accessory Module Components			
Accessory Gearbox	69	36	-
30.4 Power Turbine Module Components			
Stage 4 Nozzle Segments (All)	138	74	R
Stage 3 Nozzle Segments (All)	167	90	R
Stage 3 Disk	246	175	L,M,O,R
Stage 3 Blades (All)	246	175	L,M,O,R
Stage 4 Disk	246	175	L,M,O,R
Stage 4 Blades (All)	246	175	L,M,O,R
No. 5 Seal	186	107	E,H,M,R
No. 5 Bearing	194	114	E,H,M,R
No. 6 Bearing	186	108	E,H,M,R
Power Turbine Rotor Assembly	155	84	
30.5 Hot Section Module Components			
Combustion Liner	1170	630	P
Stage 1 Nozzle Assembly	1020	620	P
Stage 1 Blades (All)	1120	790	P
Stage 1 Disk	1120	790	P
Stage 2 Blades (All)	1130	730	P
Stage 2 Disk	1120	730	P
Stage 2 Nozzle Assembly	940	540	P
Gas Generator Turbine Assembly	940	540	P
Stage 1 Nozzle Segments (All)	2480	1080	P
Stage 2 Nozzle Segments (All)	1260	860	P
30.6 Cold Section Module Components			
No. 4 Bearing	463	246	D,G,I,M,Q
Diffuser	466	248	D,I,Q
Swirl Vane Frame	410	220	-
Compressor Stator Assembly	483	251	D,L,Q
Stage 1 Vanes (All)	3830	1980	Q
Stage 2 Vanes (All)	4520	2330	Q
Stage 3, 4, and 5 Vane Segments (All)	3170	1660	Q
Main Fuel Injectors (All)	260	130	-
No. 1 Bearing Carbon Seal	60	60	-
Output Shaft Assembly	430	240	-
No. 2 Bearing	870	570	A,B,G,T
No. 1 Bearing	910	600	A,B,F,M,T
Front Frame Assembly	322	177	C,I,J,M,Q
Inlet Guide Vanes (All)	408	226	C,I,J,M,Q
Compressor Rotor	493	259	C,D,I,J,M,Q
Centrifugal Impeller	517	273	C,D,I,J,K,L,M,Q,R
Stage 5 Blisk	518	275	C,D,I,J,K,L,M,Q,R
Stage 3/4 Blisk	525	279	C,D,I,J,K,L,M,Q,R
Stage 2 Blisk	521	278	C,D,I,J,K,L,M,Q,R
Stage 1 Blisk	531	285	C,D,I,J,K,L,M,Q,R
No. 3 Bearing	309	173	C,I,J,M,Q
No. 4 Bearing Forward Oil Seal	456	238	D,I,J,M,Q

(2) Total Time is total maintenance time with one or two mechanics.
Elapsed Time assumes two mechanics working simultaneously when practical.

There were additional requirements which the General Electric Co. imposed upon its engineering organization that also had a significant impact on the design.

- A rigid set of rules limiting and controlling the use of lockwire.
- All installed and module replacement to be accomplished with only 10 of the 182 hand tools in the A07 Army tool box.
- The engine design would not require any special tools at Aviation <u>Unit</u> Maintenance (AVUM) or Aviation <u>Intermediate</u> Maintenance (AVIM) levels.
- When oil level reading is low, the oil tank will always accept a complete quart without detrimental effect.
- The engine would require no adjustments or trimming at field maintenance, for any reason.
- Mount locations would not interfere with installed module replacement.
- No loose balance weights to be exchanged during module replacement.
- Plumbing lines shall disassemble at module flanges.
- All flanges shall have alignment features.

REQUIREMENTS PROCESS OVERVIEW

- REQUIREMENTS FOR UTTAS ENGINE DERIVED FROM 1960'S VIETNAM EXPERIENCE
- DEVELOPED JOINTLY BY GOVERNMENT AND INDUSTRY
- REDUCTION IN MAINTENANCE AND LOGISTICS SUPPORT REQUIREMENTS MAJOR OBJECTIVE FOR UTTAS
- R&M REQUIREMENTS CLEARLY STATED IN RFQ AND INCLUDED IN THE PRIME ITEM DESIGN SPECIFICATION (PIDS) WHICH WAS THE BASIS FOR THE DESIGN OF THE T700-GE-700 ENGINE.

RELIABILITY REQUIREMENTS

As a result of the experience gained in Southeast Asia with U.S. Army helicopter engines, a signficant improvement in Reliability was required for engines to be used on the next generation of U.S. Army helicopters. Several problems stand out and include:

- Scheduled engine overhaul at either 600 or 1200 hours imposed added workload on maintenance personnel and increased spare engine requirements.
- Scheduled hot-section inspections at intervals of 600 to 900 hours also created added maintenance workload and increased spare parts consumption.
- Excessive oil leakage problems.
- Excessive number of mechanical failures.
- Large number of removals for erosion and FOD.

Based on this experience, challenging and specific requirements were included in the development contract for the T700-GE-700 engine. The following are the specific reliability requirements as stated in both the PIDS #CP-2222-02000B and in the Reliability Program Plan referenced earlier.

All of these requirements required verification by the completion of the development contract or the Post Qualification Reliability Test phase which is referred to in this report as the Maturity Program.

3.40 Reliability. The engine shall achieve the specified reliability value of 1200 hours Specified Mean Time Between Failure based upon decision risks of 10 percent and a discrimination ratio of two to one. This value is subject to the failure definitions and exclusions specified in 3.40.3 and 3.40.4.

3.40.1 Engine Design Life. The engine shall have a design life of 5,000 hours, with an initial target of 1,500 engine operating hours MTBFRO (Mean Time Between Failure Requiring Overhaul) at completion of the Post Qualification Reliability Demonstration Test Program. The 1,500 hour MTBFRO is based on the criteria of "on condition" maintenance and the load spectrum below.

(a)

Percent Intermediate Engine Power	Percent Engine Life At This Power
100	15
75	45
55	25
35	10
Idle	5

(b) Two start cycles per hour, with at least half of the starts made after the engine has cooled to ambient temperature.

The basic engine and all related components shall be designed for a minimum life of 5000 hours when operated at rated temperature levels according to the loading schedule of (a) above.

3.40.1.1 Low Cycle Thermal Fatigue Design Life. All parts of the engine shall be designed to have a low cycle fatigue life of not less than 15,000 cycles. The cycle used for calculation of low cycle fatigue design life shall be as follows: In addition, the engine shall be considered to be shut down for not less than two hours between each of the above cycles for calculation of low cycle fatigue design life.

Total Time (sec)	Scheduled Time (sec)	Event
30	20	Start engine and accelerate to ground idle power.
30	10	Run at ground idle power.
36	6	Accelerate to intermediate power
96	60	Run at intermediate power.
102	6	Decelerate to ground idle power
112	10	Run at ground idle power
142	30	Shut down engine.

3.40.2 Engine Reliability Objectives. Reliability objectives to be reached at 17,000 engine operating hours of accumulated experience after qualification are shown below. These Mean Engine Operating Time Between Failure (MEOTBF) objectives shall not be degraded by more than 10 percent due to storage in approved storage container (without any maintenance or restoration) for a period not to exceed six calendar months.

Failure Classes	Engine MEOTBF (Hours)
I	1,250,000
I/II	303,000
I/II/III	6,300
I/II/III/IV	3,000
I/II/III/IV/V	1,800

3.40.3 Definitions.

(a) Mean Time Between Failure (MTBF). The total engine operating time of a population of engines divided by the total number of relevant events of engine failure experienced within the population during the measurement interval.

(b) Failure. Inability to perform required function within specified limits.

(c) Failures Requiring Overhaul (FRO). Failures in which corrective maintenance is sufficiently extensive to be beyond the capability of the Aviation Unit Maintenance (AVUM) or Aviation Intermediate Support (AVIM) level, i.e., best performed at depot level. (Typically this will include major lube system contamination cases, main engine bearing failures, etc.)

(d) Failure Classes:

Class I - Failures that result in destruction of an engine or loss of aircraft control or fire external to the engine.

Class II - Failures which result in In-Flight shutdown (i.e., unrecoverable power loss).

Class III - Failures which result in potential power losses completely or partially rectified by automatic or manual corrective action.

Class IV - Failures which result in power loss or no start.

Class V - Failure which requires unscheduled maintenance action.

(e) Power Loss. Inability to obtain and/or sustain at least 90 percent of the desired power level.

(f) Primary Failure. An independent failure, not as a result of another failure

(g) Secondary Failure. Any failure within the engine which was the result of some other failure.

3.40.4 Excluded Failures. The following exclusions apply in computation of the reliability values stated in 3.40 and 3.40.2.

(a) Failures resulting from errors of maintenance personnel.

(b) Failures resulting from operating the engine beyond specification limits. Included failures are those operationally related failures for which engine provides integral protective devices (overspeed, overtemperature, hot starts).

(c) Failures resulting from airframe components

(d) Failures to start if a successful start is accomplished without corrective maintenance action.

(e) Reported operating malfuctions which cannot be verified by subsequent investigation, flight or ground test.

(f) Multiple part removals and other maintenance actions performed upon the same engine following an initial failure requiring maitenance action will be counted as one failure against the engine.

(g) Failures of equipment not furnished by the Contractor.

(h) Failures for which a corrective engine design change or an operational procedure change has been demonstrated, and approved by the Government, will be removed from the failure count, unless the events are identical to those for which corrective action was taken and it has been determined that the prescribed corrective action procedures have been utilized.

RELIABILITY REQUIREMENT

- LESSONS LEARNED IN VIETNAM USED AS A BASIS FOR SETTING RELIABILITY REQUIREMENTS FOR UTTAS ENGINE.
- RELIABILITY REQUIREMENTS, BOTH QUANTITATIVE AND QUALITATIVE, VERY SPECIFICALLY SPELLED OUT IN PIDS AND R&M PROGRAM PLANS.
- ALL REQUIREMENTS WERE REQUIRED TO BE DEMONSTRATED BY END OF THE DEVELOPMENT/QUALIFICATION PROGRAM OR MATURITY PROGRAM.

RELIABILITY REQUIREMENTS (CONTINUED)

- R&M REQUIREMENTS WERE CONTRACTUAL REQUIREMENTS FOR THE T700-GE-700 ENGINE AND NOT JUST GOALS.
- REQUIREMENTS BOTH QUALITATIVE AND QUANTITATIVE.
- REQUIREMENTS WERE STATED CLEARLY AND IN DETAIL.
- VERIFICATION OF REQUIREMENTS A CONTRACTUAL COMMITMENT.
- REQUIREMENTS MUCH MORE DETAILED AND SPECIFIC THAN ANY PRIOR ENGINE DEVELOPMENT PROGRAM.
- REQUIREMENTS WERE REALISTIC YET CHALLENGING WHEN COMPARED TO HELICOPTER ENGINES OF THE 1960's.

MISSION PROFILE ESTABLISHMENT

MISSION PROFILE ESTABLISHMENT

In defining the life requirements of an Aircraft Gas Turbine Engine such as the T700, it is necessary to define the predicted mission usage in terms of percent of operating time at various power settings (stress rupture life) and the required low cycle fatigue life. With these requirements defined, the design engineer can then define his assigned component design to meet these criteria.

As easy as this may sound, defining realistic mission requirements in advance of the actual system fielding is a very difficult task. *If the time at max power*, for example, is overstated significantly then parts may be overdesigned which can affect cost and weight. If, on the other hand, mission requirements are underestimated in the PIDS, certain parts might be designed such that they fail short of meeting the stated overall life requirements which could require costly redesign at a future point in time.

In paragraph 3.40.1 of the PIDS, the Engine Design Life Requirement was defined in the classic terms of percent time or life at a designated power level defined in a percent of intermediate power. This in effect defined a mission usage profile and was the original basis for designing the various engine components to meet 5000 hour minimum life. This power spectrum profile coupled with the LCF requirement of 15,000 cycles as defined in paragraph 3.40.1.1 of the PIDS (as shown on the following page) provided the original mission profile for the engine design.

3.40.1 Engine Design Life. The engine shall have a design life of 5,000 hours, with an initial target of 1,500 engine operating hours MTBFRO (Mean Time Between Failure Requiring Overhaul) at completion of the Post Qualification Reliability Demonstration Test Program. The 1,500 hour MTBFRO is based on the criteria of *"on condition"* maintenance and the load spectrum below.

(a)

Percent Intermediate Engine Power	Percent Engine Life At This Power
100	15
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Idle	5

(b) Two start cycles per hour, with at least half of the starts made after the engine has cooled to ambient temperature.

The basic engine and all related components shall be designed for a minimum life of 5000 hours when operated at rated temperature levels according to the loading schedule of (a) above.

3.40.1.1 Low Cycle Thermal Fatigue Design Life. All parts of the engine shall be designed to have a low cycle fatigue life of not less than 15,000 cycles. The cycle used for calculation of low cycle fatigue design life shall be as follows: In addition, the engine shall be considered to be shut down for not less than two hours between each of the above cycles for calculation of low cycle fatigue design life.

MISSION PROFILE OVERVIEW

- REALISTIC MISSION USAGE PREDICTION NEEDED TO DESIGN AN AIRCRAFT GAS TURBINE ENGINE TO MEET SPECIFIED LIFE REQUIREMENTS.
- PREDICTING ACTUAL MISSION PROFILE BEFORE SYSTEM IS FIELDED IS DIFFICULT TASK.
- MISSION PROFILE FOR T700 DEFINED IN PIDS IN PERCENT OF ENGINE LIFE AT VARIOUS POWER SETTINGS. IN ADDITION, ENGINE HAD TO BE DESIGNED TO MEET 15000 CYCLES LCF LIFE.

Before embarking into a discussion of mission profile simulated testing in the factory development program, it is important to understand certain acronyms used in discussing life usage parameters on an aircraft gas turbine engine.

EQUIVALENT LOW CYCLE FATIGUE (ELCF) CYCLE

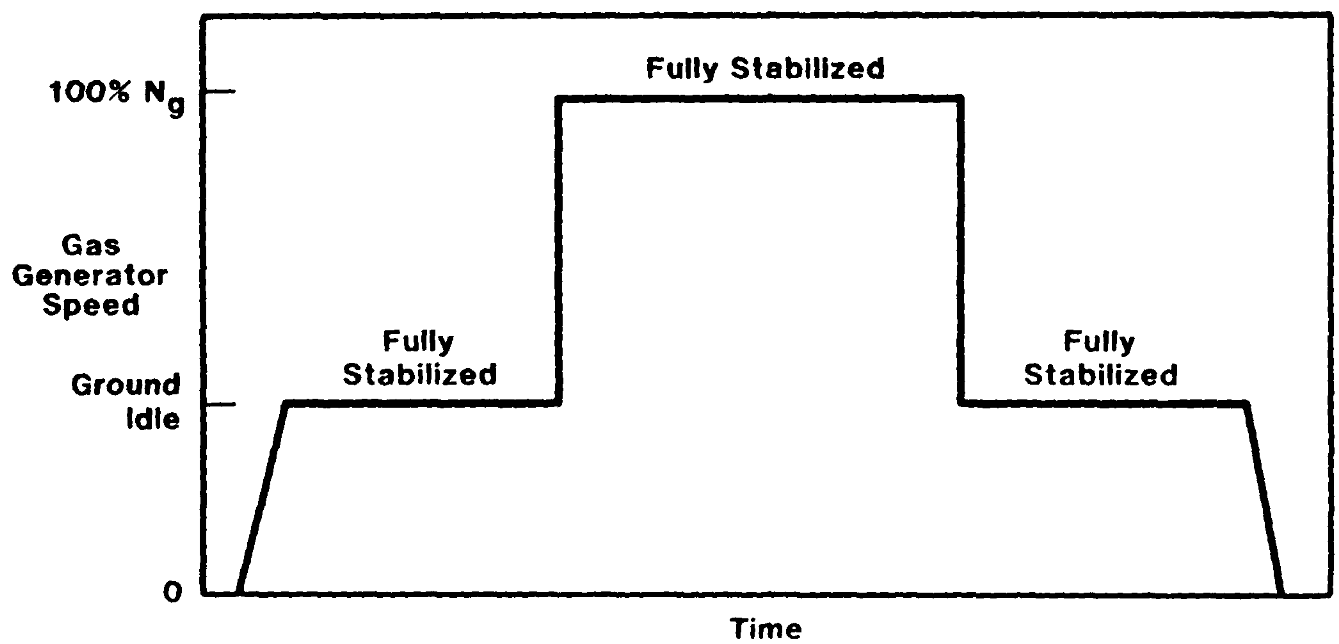
An ELCF cycle, shown on Page IIC-31, is defined as an engine operating cycle beginning from cool engine shutdown, engine start and acceleration to ground idle, acceleration to 100% gas generator speed, deceleration to ground idle and shutdown. At each plateau and following shutdown, sufficient time is allowed for all thermally induced stresses to stabilize as shown on Page IIC-33. For the T700 engine two minutes is generally sufficient for stabilization of the stress cycle.

The ELCF life of each rotating engine component can be determined in terms of ELCF cycles. For example, the turbine disks may have a life of 15,000 ELCF cycles and the compressor disks may have a life of 25,000 ELCF cycles.

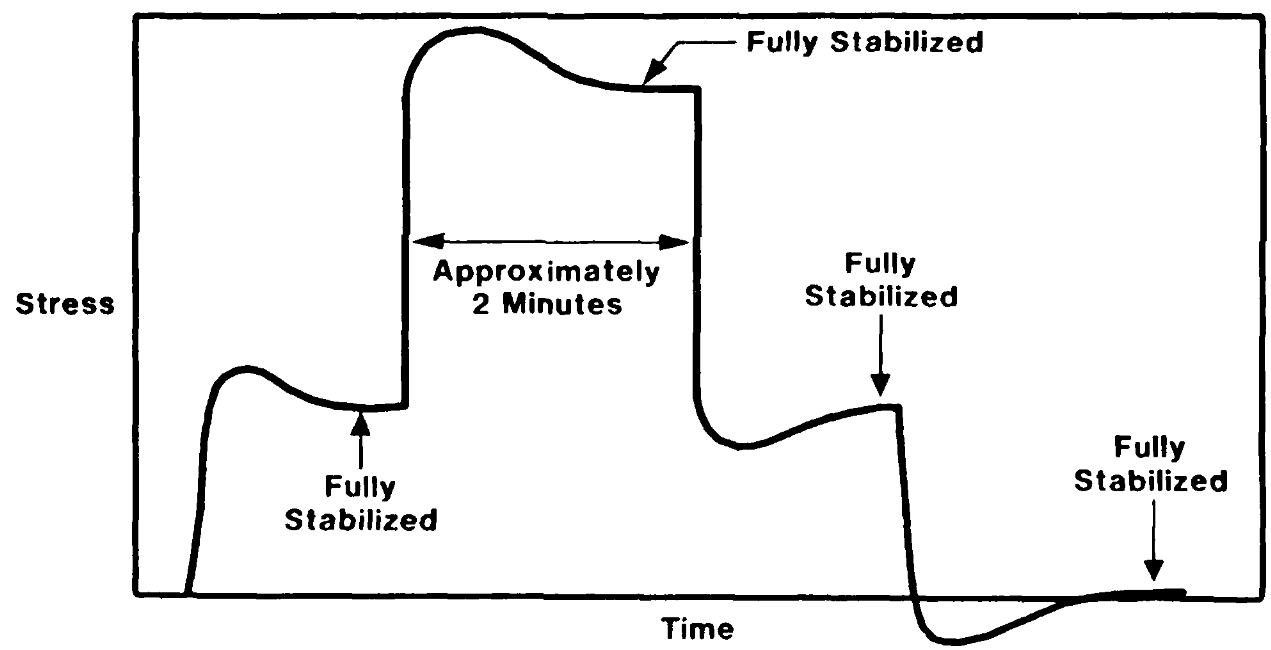
The ELCF cycle forms a common denominator for expressing LCF life. Any engine operating or test cycle can be expressed in terms of ELCF cycles when considering LCF damage. For instance, a given mission cycle might be defined. If the turbine disk has a life of 15,000 ELCFs and can last for 30,000 or the defined mission cycles, then it can be said that each mission cycle is equivalent to one-half (0.5) ELCF. If, on the other hand, the turbine disk could only last for 7,500 of the defined mission cycles, then each mission cycle would be equivalent to two (2.0) ELCFs.

Low Cycle Fatigue Damage

Equivalent Low Cycle Fatigue Cycle (ELCF)



ELCF Stress Cycle



EQUIVALENT FULL THERMAL CYCLES (EFTC)

For static engine components such as turbine nozzles and combustion liners whose LCF life is consumed primarily by thermally induced stress cycles, an EFTC cycle is defined in a manner similar to the ELCF. Page IIC-35 shows an EFTC cycle which is defined as an acceleration from ground idle to maximum engine turbine temperature and back to ground idle. Again, sufficient time is allowed at each plateau for thermal stresses to stabilize. Engine component life may be determined in terms of EFTCs and likewise any engine cycle can be expressed in terms of EFTCs. For example, if a turbine nozzle with a life of 25,000 EFTCs could only withstand 12,500 defined mission cycles, then each mission cycle would be equivalent to 2 EFTCs.

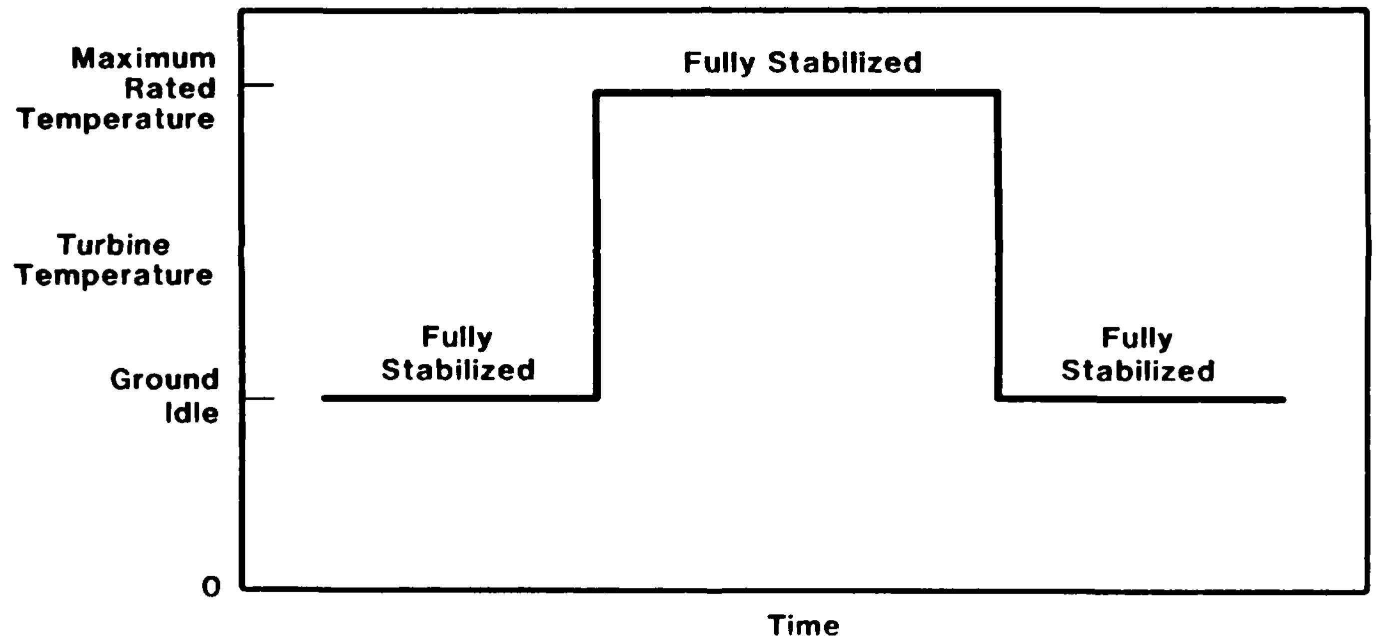
EQUIVALENT TIME AT MAXIMUM POWER (ETAMP)

For parts whose lives are primarily affected by creep and stress rupture damage, life can be expressed in terms of ETAMP, as shown on Page IIC-37. By definition, 1 ETAMP is 1 hour of engine operation at maximum rated temperature. If a turbine bucket with a life capability of 500 ETAMP hours could last for 5,000 hours of defined mission cycles, then each hour of the mission cycle would be eqivalent to 0.1 ETAMP hour.

Thermal Cycle Damage

Equivalent Full Thermal Cycle (EFTC)

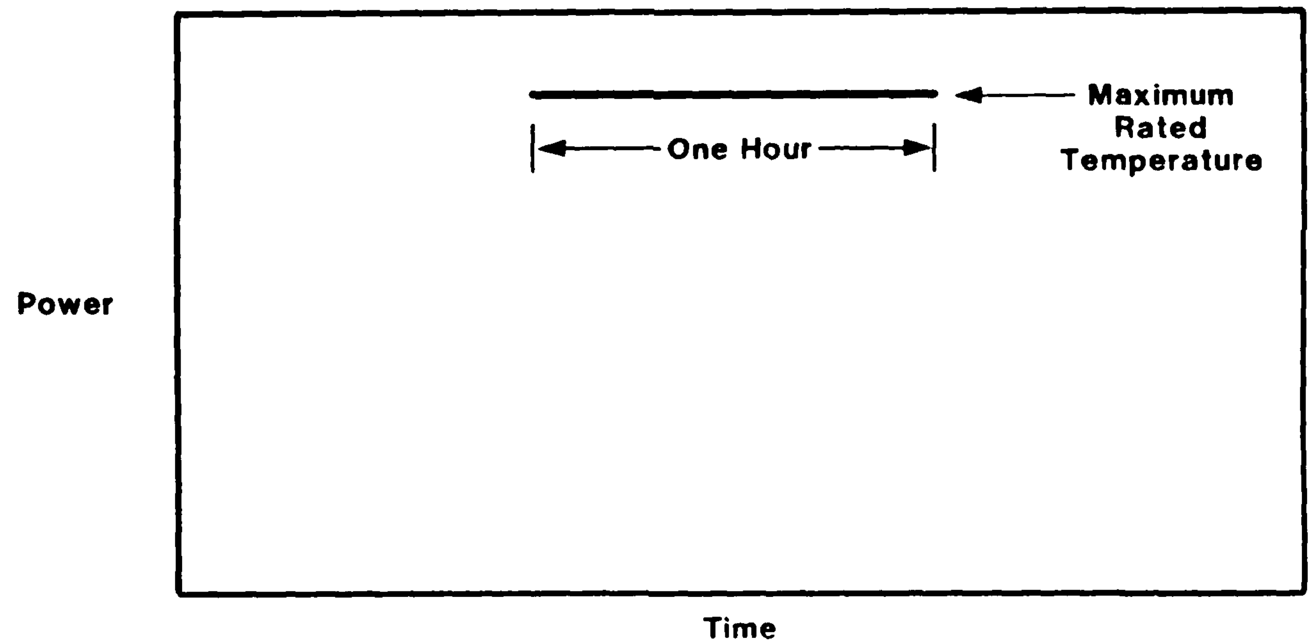
Sea Level Static, Standard Day, Average Service Engine



Stress Rupture Damage

Equivalent Time at Maximum Power (ETAMP)

Sea Level Static, Standard Day, Average Service Engine



Throughout the Development/MOT program, two basic endurance cycles were utilized. These included the MOT cycle and LCF cycle. The MOT cycle which was specified in paragraph 4.5.1.7 of the PIDS is presented in Page IIC-39 and was designated as the official endurance test cycle for the T700.

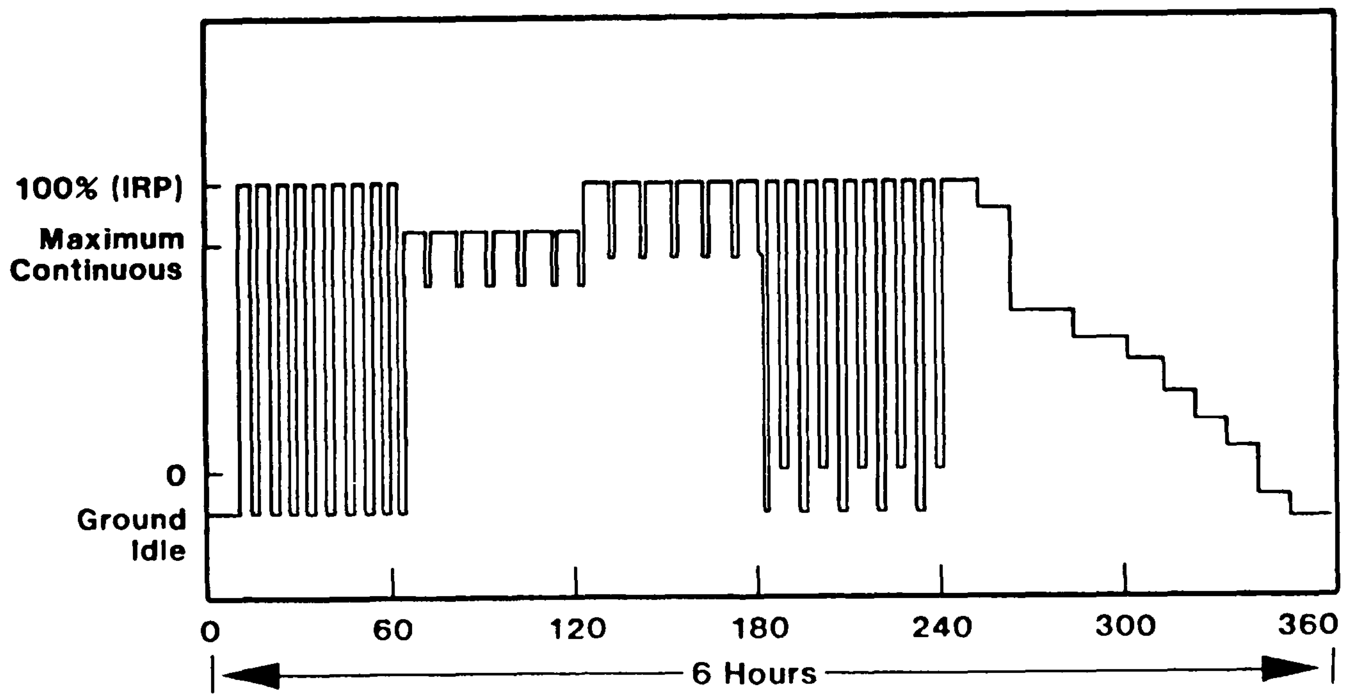
This test cycle contains a significant number of throttle excursions between Ground Idle, Maximum Continuous and IRP as well as subjecting the engine to maximum temperature operation for 48 percent of the time. While this test cycle is six times more severe than qualification test cycles of the 1950s and 1960s, the relationship of ELCF, EFTC and ETAMP damage is significantly out of proportion when compared to the intended field usage, the so-called U.S. Army Black Hawk helicopter 10 mission mix.

A comparison of the life usage parameters for the MOT cycle and the Black Hawk 10 mission mix is as follows;

Engine Component	MOT TO 10 Mission Mix Severity
Stage 2 Turbine Disk	1/2 to 1 (ELCF)
Stage 1 Turbine Bucket	35.6 to 1 (ETAMP)
Stage 1 Turbine Nozzle	67.4 to 1 (EFTC)

As seen from the above comparison, the MOT cycle exercises the Stage 1 turbine bucket at an acceleration factor of 35.6 to 1 and almost 70 times more severely than the Stage 1 turbine disk which has an acceleration factor of only 1/2 to 1 relative to 10 mission mix operation. A more sonable relationship would be desirable since at the end of 150 hours of MOT testing th age 1 turbine bucket has been exercised the equivalent of (35.6 x 150 hours) 5,340 hou 10 mission mix operation whereas the turbine disk has hardly been exercised at all, ving only seen the equivalent (0.5 x 150 hours) 75 hours of 10 mission mix operation.

Endurance Cycle



The LCF cycle shown in Page IIC-41 is called out in paragraph 4.5.9 of the PIDS and was required as the official LCF demonstration test for the T700 engine. This cycle stresses ELCF and full thermal cycles (FLTC) at the expense of ETAMP.

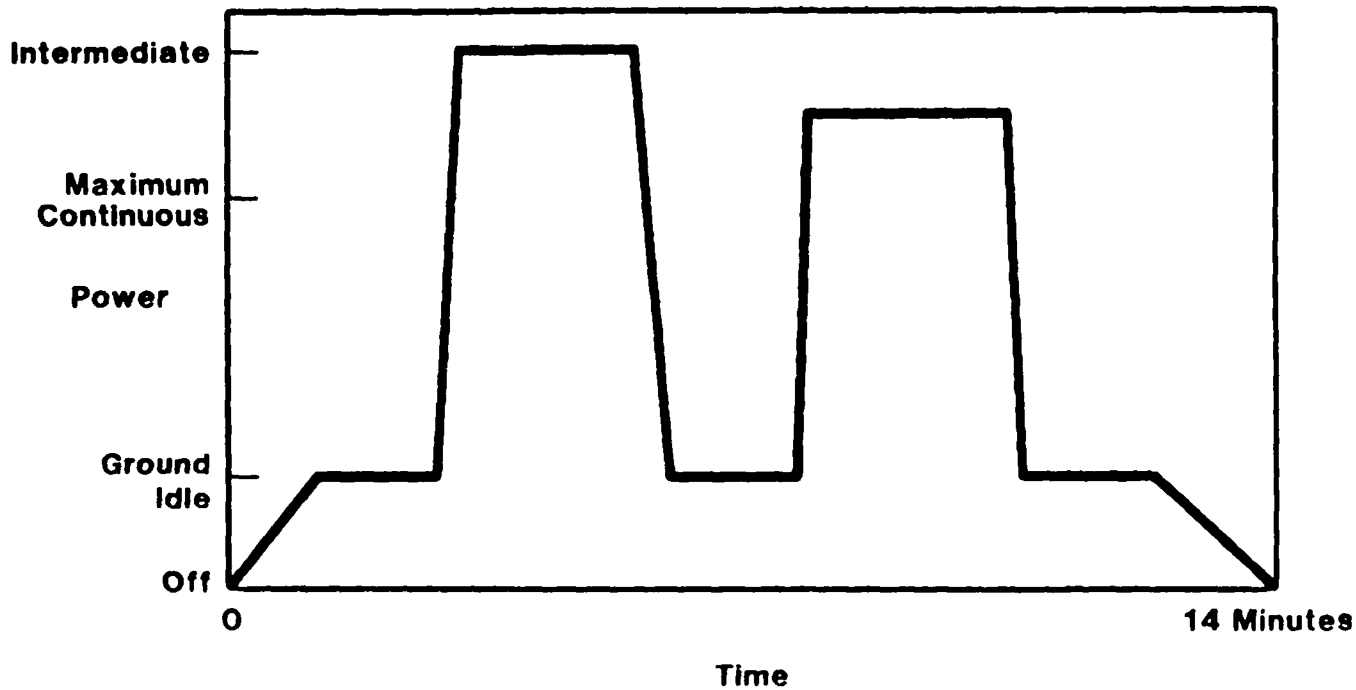
As the development program got underway, it was obvious that the 15% life requirement at Intermediate Rated Power was unrealistic in terms of actual field use of a twin engine helicopter such as the Black Hawk. Gradually, information was made available through the Black Hawk Project Manager's Office (PMO) defining a total of ten (10) different operational missions for the Black Hawk aircraft, examples of which are shown graphically on Page IIC-41, 42 and 43.

Also specified will be the percentage of time each mission is to be flown, along with representative ambient conditions of altitude and outside air temperature. In the example missions, mission 7 is to be flown 15% of the time, mission 8, 60% of the time and mission 9, 25% of the time.

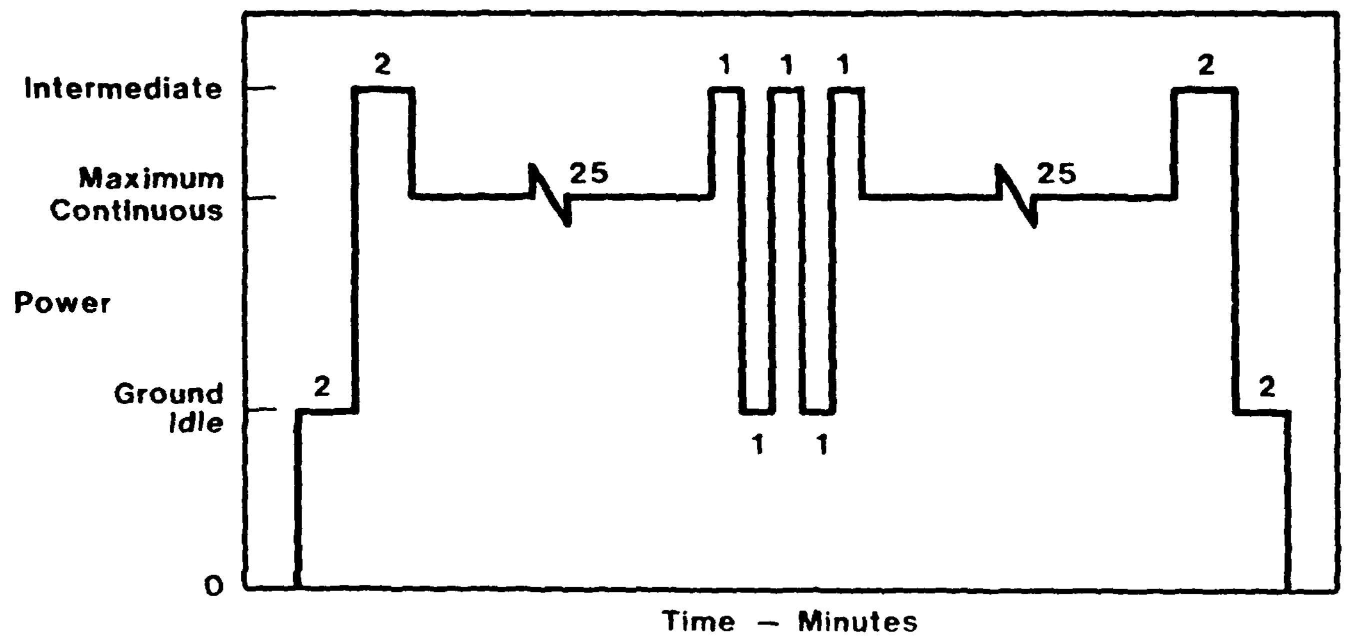
Each mission cycle can be described by a tabulation of the number of throttle excursions between various power levels and the amount of time spent at each power level. For the example missions, this tabulation is shown on Page IIC-45.

By using the percentage of time that each mission is flown as weighting factors, a composite tabulation of all the missions can be constructed by forming a weighting average of the throttle excursions between various power levels and time at power. For the example missions, this composite tabulation is shown on Page IIC-45.

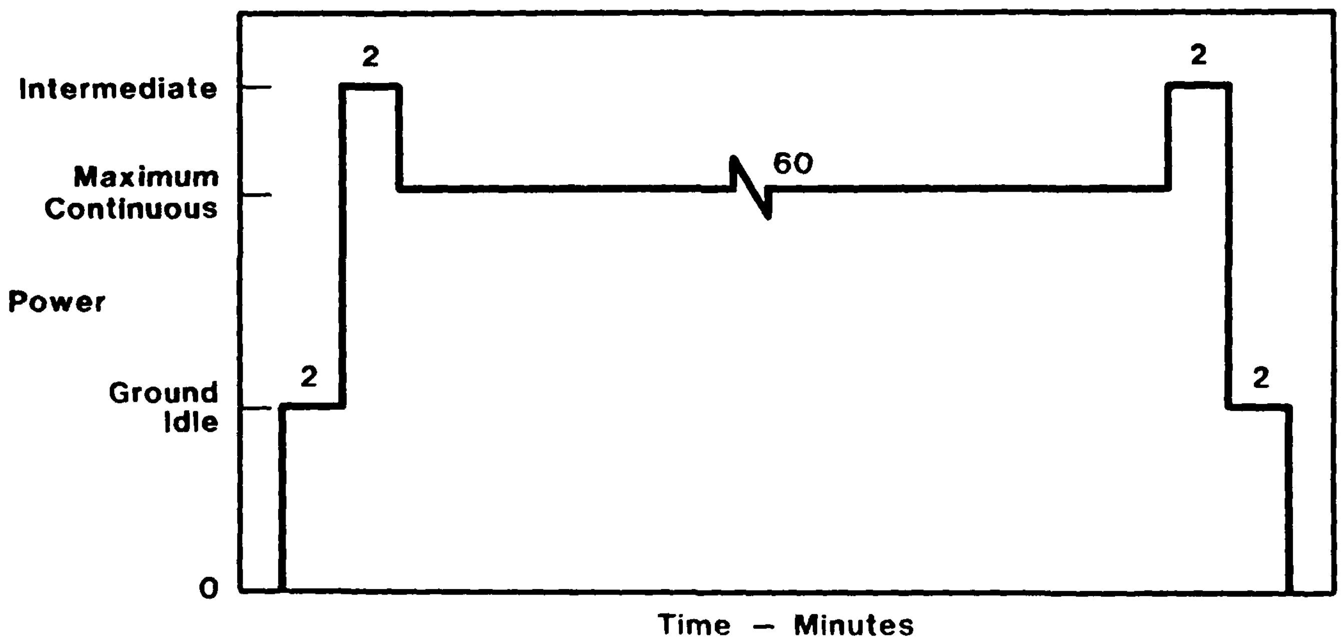
Low Cycle Fatigue Cycle



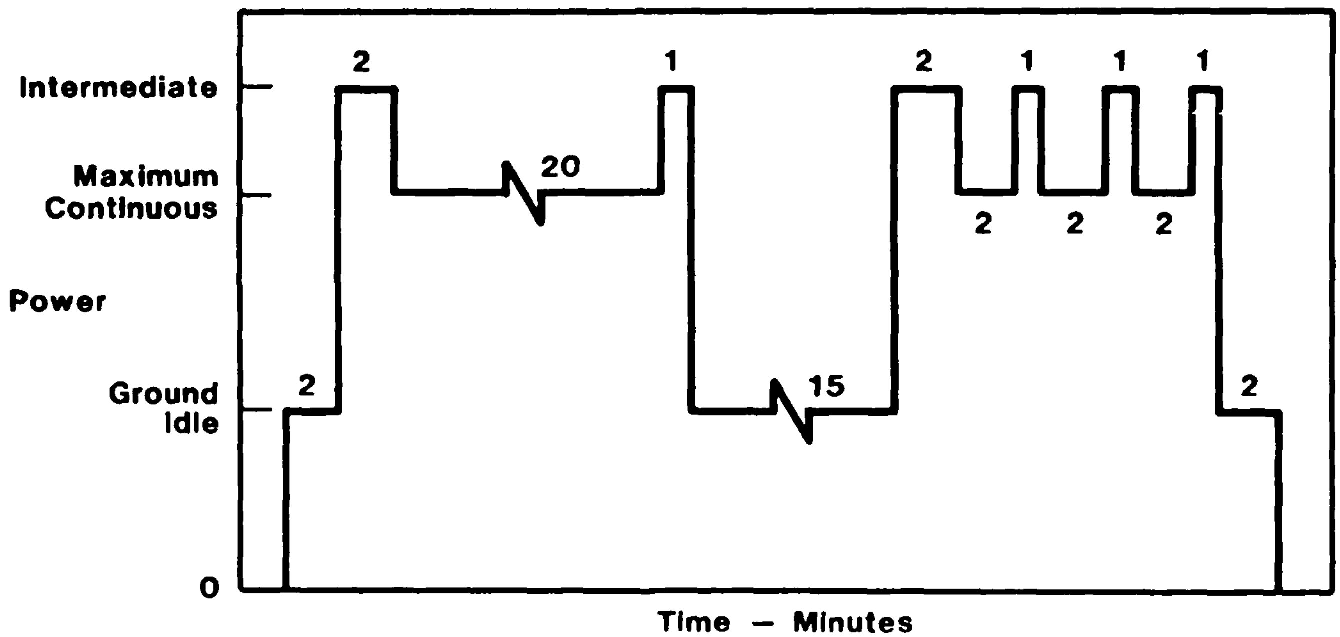
Medical Evacuation Mission
15 Percent



Ferry Mission
60 Percent



Troop Escort Mission
25 Percent



GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

Table I. Tabulation of Throttle Excursions and Time at Power

	Throttle Excursions			Time at Power (Minutes)			
Mission	0-IRP-0	GI-IRP-GI	MC-IRP-MC	GI	MC	IRP	Percent of Time Mission Flown
#7	1	2	2	6	50	7	15%
#8	1	0	1	4	60	4	60%
#9	1	1	4	19	26	8	25%

IRP = Intermediate Rated Power
MC = Maximum Continuous Rated Power
GI = Ground Idle
O = Shutdown

Table II. Composite Tabulation of Throttle Excursions and Time at Power

Throttle Excursions			Time at Power (Minutes)		
0-IRP-0	GI-IRP-G1	MC-IRP-MC	GI	MC	IRP
1	0.55	1.9	8.05	5.0	5.45

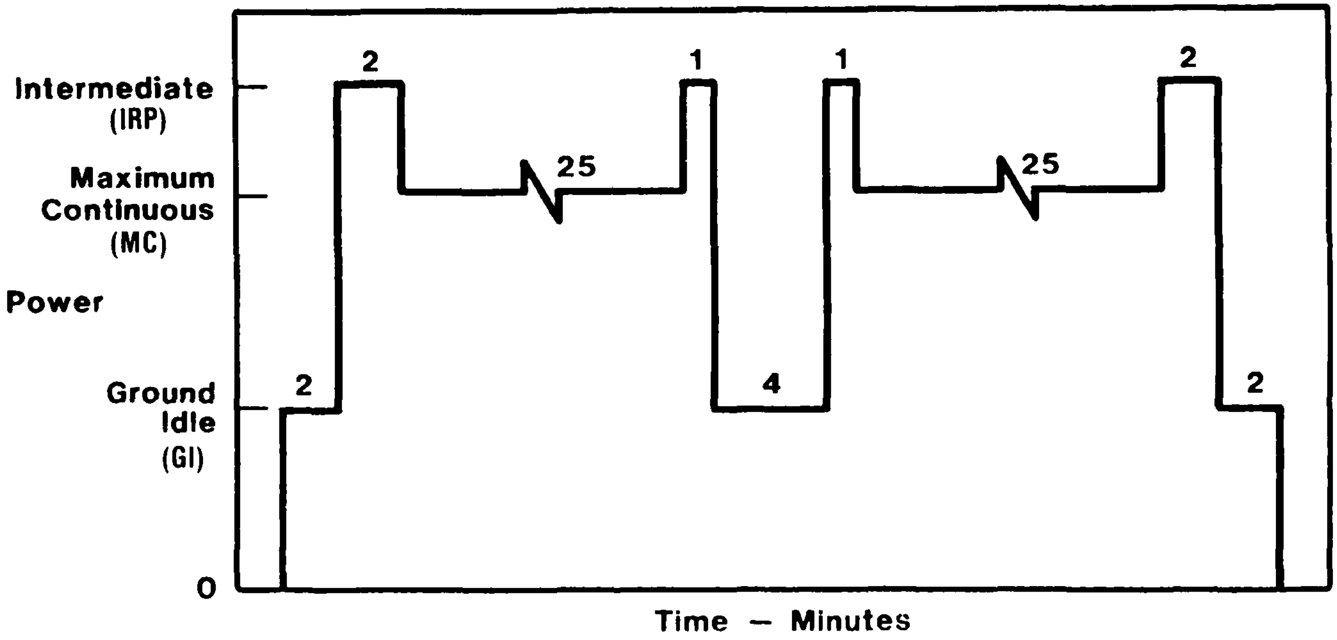
A composite mission cycle can then be constructed using the composite tabulation which will represent the mix of all the missions specified. For the example missions the composite mission is shown on Page IIC-47.

It may not be possible to exactly match the composite mission cycle with the composite tabulation because of fractional throttle excursions. In practice the less damaging fractional values are rounded up to give a composite mission cycle that will be at least as severe as the composite tabulation.

The composite mission cycle, termed the Simulated Mission Endurance Test or SMET cycle, represents a mission which could be flown for 5,000 hours and which would consume the same engine life as 5,000 hours of flying the actual missions in the proportions specified. This SMET engine cycle could also be used to exercise an engine in a test cell and one hour of test cell time would be equivalent to one hour of field usage.

For each of the example mission cycles, the ELCF, EFTC and ETAMP content for each engine component can also be determined. If the SMET mission has been properly constructed, the ELCF, EFTC and ETAMP content of the SMET mission cycle will equal the weighted averages of the ELCF, EFTC and ETAMP from the field mission cycles.

Composite Mission Cycle
Simulated Mission Endurance Test (SMET)



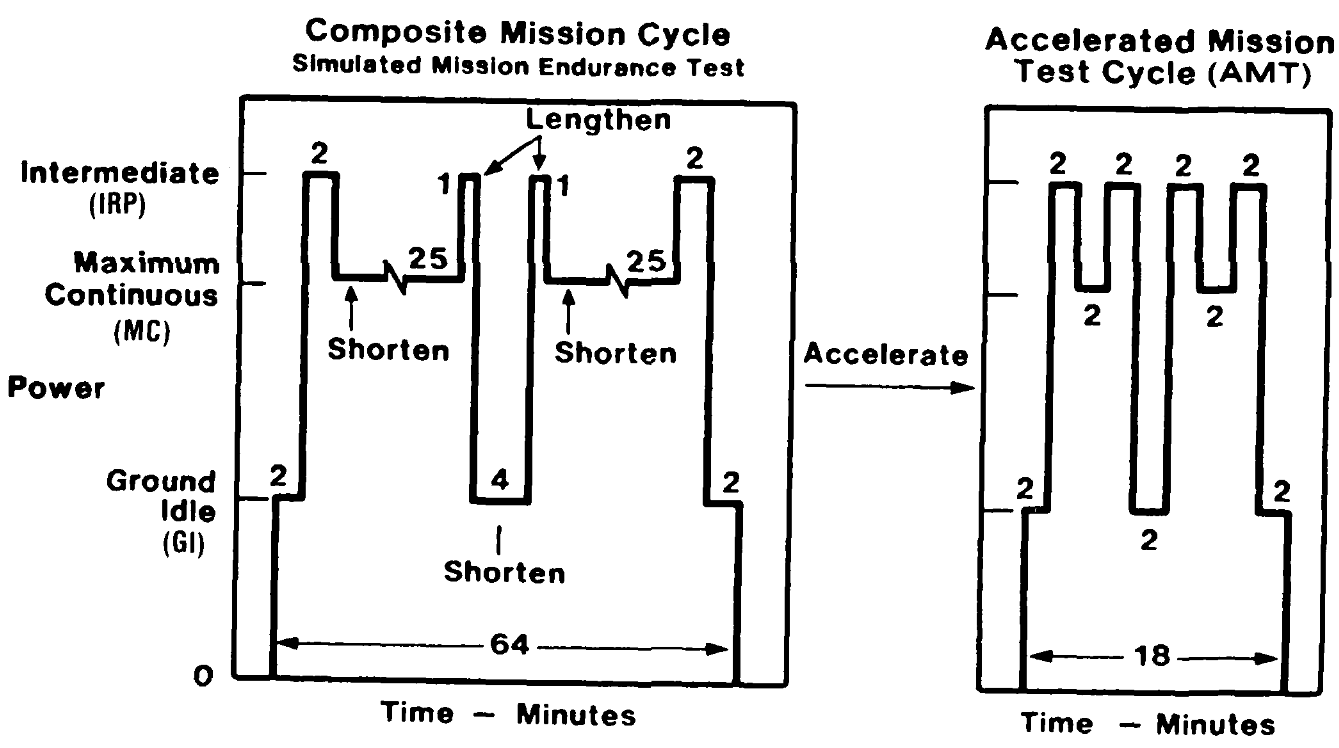
ACCELERATED MISSION TEST (AMT) CYCLE

It has been stated that the SMET mission cycle could be used to exercise an engine in a test cell with a one to one severity relationship between test cycle and field usage. Because of the high costs associated with engine testing and the time required to exercise an engine through an entire life time, e.g., 5,000 hours, it is desirable to shorten the engine test time while still maintaining the ELCF, EFTC and ETAMP damage content at the same proportional levels as in the composite mission. This acceleration of the composite mission test cycle is accomplished by deleting non-damaging portions of the cycle as shown on Page IIC-49.

By eliminating two minutes at GI, 46 minutes at MC, and by adding two minutes at IRP, the SMET mission cycle can be shortened from 64 minutes to 18 minutes. Note that the various throttle excursions have been preserved in transforming the SMET cycle to the AMT, thus preserving the ELCF and EFTC content. The ETAMP content was preserved by adding two minutes at IRP to maintain the stress rupture damage that was eliminated by the deletion of 46 minutes at MC and two minutes at GI. Note that the times following each throttle excursion were not shortened to less than two minutes to ensure that all thermal stresses have time to stabilize.

Since the accelerated mission test cycle contains the same ELCF, EFTC and ETAMP damage as the SMET cycle but requires a fraction of the time, this cycle can now be used to exercise an engine in the test cell and one hour of running would be equivalent to approximately 3.5 hours of field operation, hence the name Accelerated Mission Test (AMT) cycle. This particular AMT cycle would have an acceleration factor of about 3.5 to 1.

AMT Cycle Construction



Notice that in the Accelerated Mission Test cycle the proportional relationship between ELCF, EFTC and ETAMP damage content has not been disturbed. This is important in accelerated mission testing so as not to over-exercise one engine component while others are not exercised sufficiently. For example, if the AMT cycle had been constructed to accumulate 10 times more ETAMP damage than in the actual engine mission cycles, the turbine blades might have to be changed out ten times during a test to exercise other components through just one engine life-time. This would add substantial expense to the engine test program with little added benefit. A properly constructed AMT cycle exercises all engine components in the same relationship that they will be exercised in the field.

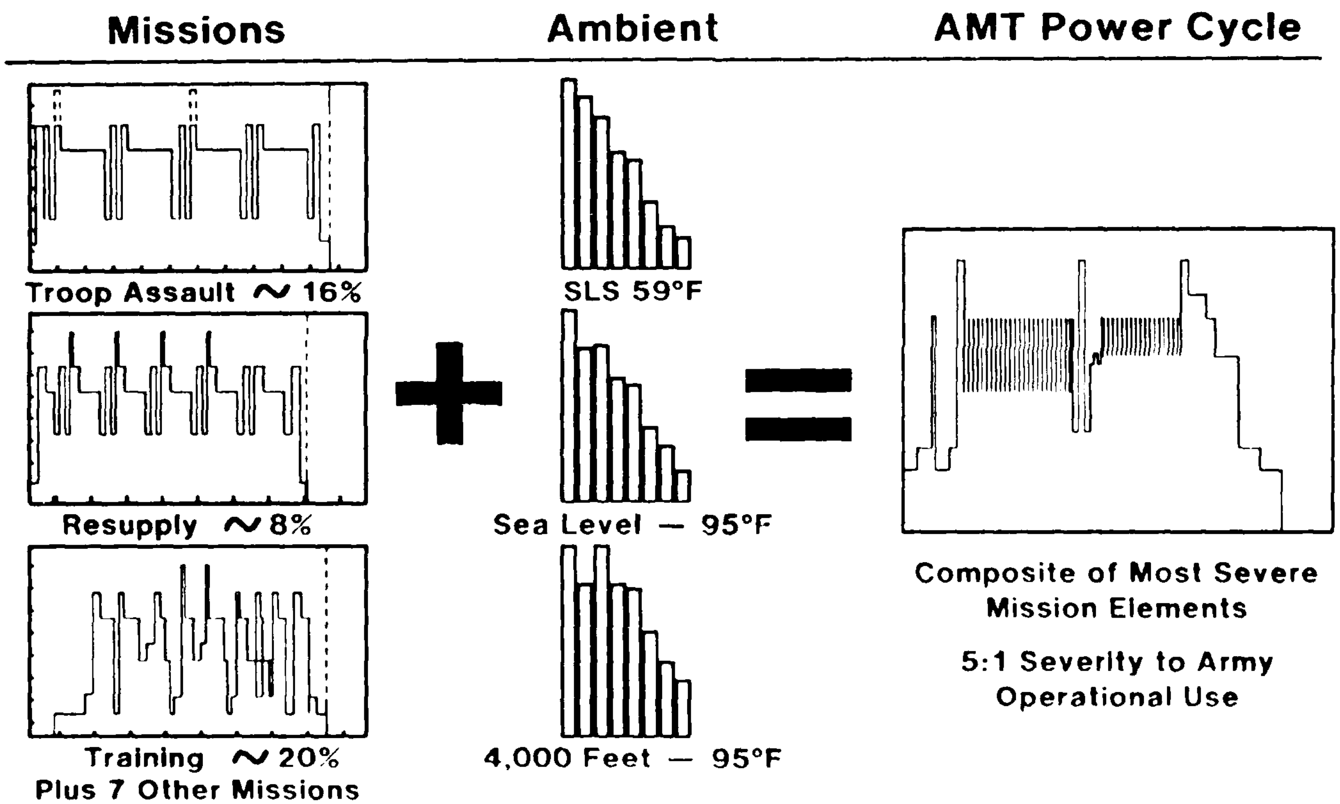
In subsequent T700 accelerated mission tests, such as the Accelerated Simulated Mission Endurance Test (ASMET) and the Accelerated Mission Test (AMT), a significant improvement in the balance of operational severity was achieved as shown by the comparisons below.

A comparison of the ASMET test cycle severity with the 10 mission mix for selected engine components is as follows:

Engine Component	ASMET To Black Hawk 10 Mission Mix Severity
Stage 2 Turbine Disk	2 to 1 (ELCF)
Stage 1 Turbine Bucket	5 to 1 (ETAMP)
Stage 1 Turbine Nozzle	3 to 1 (EFTC)

The T700 AMT test cycle is shown on Page IIC-51 and the comparison of test cycle severity with the 10 mission mix is provided on Page IIC-52.

T700 AMT Cycle



The AMT acceleration factor is approximately two times that of the ASMET cycle and again the severity is well balanced between ELCF, EFTC and ETAMP.

A comparison of AMT Cycle Severity to Black Hawk 10 Mission Mix is as follows:

Engine Component	AMT To Black Hawk 10 Mission Mix Severity
Stage 2 Turbine Disk	4.75 to 1 (ELCF)
Stage 1 Turbine Bucket	7.08 to 1 (ETAMP)
Stage 1 Turbine Nozzle	9.95 to 1 (EFTC)

The Accelerated Mission Test cycle, however, provides a balance between ELCF, EFTC, and ETAMP which is representative of field mission usage and from an economical point of view it is this test cycle which provides the most information on all engine parts at the least test cost.

REQUIREMENTS DEVELOPMENT SUMMARY

- MISSION PROFILE AND LCF LIFE WERE SPECIFIED IN THE ORIGINAL PIDS. (PROFILE WAS IN TERMS OF % LIFE AT DESIGNATED POWER LEVELS.

- LATER INPUTS INDICATED ACTUAL MISSION USAGE TO BE MUCH LESS SEVERE IN TERMS OF TIME AT IRP.

- MORE REALISTIC MISSION PROFILES WERE DEFINED AFTER THE DEVELOPMENT TEST PROGRAM WAS COMPLETED AND THESE MISSION REQUIREMENTS WERE COMPRESSED/CONSOLIDATED INTO A SIMULATED MISSION CYCLE.

- BY FURTHER MODIFICATION AN ACCELERATED MISSION CYCLE WAS FORMULATED FOR USE IN THE MATURITY AND FOLLOW-ON COMPONENT IMPROVEMENT PROGRAMS.

DESIGN ALTERNATIVE STUDIES

From the very outset of the T700 Development Program, which had its beginning in the ATE(GE12) Demonstrator Program, design trade-off studies were utilized to optimize engine design from the standpoint of meeting technical requirements for the T700 gas turbine engine.

The following is a discussion of some of the more significant trade-off studies conducted in the evolution of the T700 design.

DESIGN TRADE OFFS

- COST
- SPEC. REQUIREMENT (RELIABILITY)
- MAINTAINABILITY
- WEIGHT
- INDUSTRY STANDARD
- QUALITY CONTROL
- MANUFACTURABILITY

PART "DESIGN"

Integral Inlet Particle Separator

During early U.S. Army Operational experience, turboshaft inlet separators were provided principally as airframe parts of the total installation. Most proved less than satisfactory, because of operational and maintenance problems. General Electric gained much experience with inlet separator in its T58 and T64 engine installations and initiated designs in the early 1960s. It was concluded from these studies that an integral separator could be most efficiently designed as part of the engine. Moreover, performance and operation of the engine would then be solely the responsibility of the engine manufacturer.

When the inlet separator is designed as an integral part of the engine rather than a bolt-on kit is can also perform several other useful functions. The T700 separator performs all of the following functions:

- Separates 85-90% of all sand and dust particles.
- Provides about 90% protection against FOD from stones, ice, metal particles, sticks, leaves, etc.
- Provides oil tank storage.
- Performs air/oil cooling function
- Self-contained scavenge blower system can also provide supplemental bay cooling.
- Acts as the supporting engine front frame.
- Mounts the accessory gearbox.
- Provides main engine front mounts.

The IPS provides the engine with an improved capability to operate in the Army field environment with enhanced safety, higher reliability, and reduced maintenance burden.

INTEGRAL INLET PARTICLE SEPARATOR

- EARLY INLET PARTICLE SEPARATORS 'BOLT-ON' DESIGN.
- MANY OPERATIONAL AND MAINTENANCE PROBLEMS.
- TRADE-OFF STUDY SHOWED INTEGRAL DESIGN TO HAVE GREATEST 'PAY-OFF'.
- INTEGRAL IPS PERFORMS MULTI-FUNCTIONS.
- PROVIDES VASTLY IMPROVED CAPABILITY TO OPERATE IN 'HOSTILE' ENVIRONMENT.

Top Mounted Controls and Accessories

Gas turbine engines of the 1960's conventionally had accessory gearboxes and associated controls and accessories mounted on the bottom of the engine. Experience in Vietnam with U.S. Army helicopters showed a high rate of engine damage resulting from small arms fire from the ground hitting various critical controls and/or service lines near the bottom of the engine. Studies also showed that accessibility and ease of maintenance were significantly enhanced by top mounting the accessories and accessory drive.

TOP MOUNTED CONTROLS AND ACCESSORIES

- 1960 HELICOPTER ENGINES USED BOTTOM MOUNTED ACCESSORY DRIVES.
- VIETNAM SHOWED HIGH RATE OF ENGINE ACCESSORY DAMAGE DUE TO SMALL ARMS FIRE.
- TRADE-OFF STUDY SHOWED REDUCED VULNERABILITY TO SMALL ARMS FIRE WITH TOP-MOUNTED ACCESSORIES IN ADDITION TO IMPROVED ACCESS FOR EASIER MAINTENANCE.

Axi-Centrifugal Compressor

In the very early advanced component test program of the mid 1960's, numerous design trade studies were made on the optimum compressor configuration to be pursued for the next generation of helicopter engines in the 1500 SHP class.

A driving objective was to minimize the number of individual parts making up the compressor while maximizing its ruggedness and durability. Based on the need for a high pressure ratio compressor to improve cycle efficiency, an all axial compressor design was discarded due to the very small size of the blades in the aft stages coupled with the inherent problem of clearance control. This decision led to the combination of the axial-centrifugal design of the T700 compressor.

Another trade off design study was conducted on replaceable compressor blades in the axial stages vs. the 'blisk' design in which the blades are machined into the wheel. With the built-in particle separator providing improved protection for the compressor coupled with the simplicity of rotor assembly/disassembly, the decision was made to go with the blisk construction. Thus the T700 axial compressor design evolved with only 11 major parts.

- AXI-CENTRIFUGAL COMPRESSOR DESIGN EVOLVED FROM TRADE-OFF STUDIES AIMED AT OPTIMIZING:

  - PERFORMANCE
  - STALL MARGIN
  - FEWEST MOVING PARTS
  - RUGGEDNESS
  - DURABILITY
  - EASE OR ASSEMBLY

- 'BLISK' DESIGN CHOSEN OVER REPLACEABLE BLADE DESIGN BASED ON:

  - IMPROVED AERO-MECHANICAL CHARACTERISTICS
  - SIMPLICITY OF ASSEMBLY/DIS-ASSEMBLY
  - REDUCTION IN INDIVIDUAL PARTS
  - IMPROVED PROTECTION AFFORDED BY INTEGRAL IPS

Combustor

A significant trade-off study was conducted on this very critical component. Conventional combustors of the 1960's were, for the most part, fabricated shells with duplex vaporizing fuel nozzles. Pattern Temperature Factors (PTF) or exit temperature profile variations were generally high resulting in poor hot section durability. These type combustors were low cost to manufacture but had very poor durability. After reviewing the Life Cycle Cost studies, it became obvious that the more expensive machined ring design incorporating central fuel injectors with inherently better PTF's and cleaner combustion provided a much lower LCC than the lower cost fabricated design.

To date, not a single T700 combustor has been replaced in over 300,000 flight hours in the Black Hawk.

COMBUSTOR

- COMBUSTOR'S IN 1960 ENGINES WERE LOW COST, FABRICATED SHEET METAL DESIGNS WITH 600 TO 900 HOUR LIFE.
- TEMPERATURE PROFILE VARIATIONS (PTF) FROM THESE COMBUSTORS WERE HIGH RESULTING IN POOR HOT SECTION DURABILITY.
- TRADE-OFF STUDIES SHOWED THE MACHINED RING DESIGN WITH A CENTRAL INJECTOR SYSTEM HAD A MUCH LOWER LIFE CYCLE COST THAN THE LOWER COST FABRICATED DESIGN.

Gas Generator Turbine

The overall design approach for the T700 gas generator turbine was to incorporate the proven GE12 demonstrator turbine with minimum design changes to meet the life, performance, maintainability and design-to-cost requirements defined by the U.S. Army. Therefore, the two-stage, air-cooled, high pressure turbine operates at the same temperature level as the GE12 and uses the same conservative cooling concepts as in the GE12. A more complicated turbine blade cooling scheme was rejected in favor of maintaining the simple radial convection system. Anticipated savings in cooling flow were marginal when compared with the greater risk, cost and lower reliability of more complicated systems.

Power Turbine

The T700 power turbine is a two stage, high performance design with an output speed at 20,000 rpm. It followed the same aerodynamic design philosophy and has similar mechanical features as the GE12. Turbine inlet temperature for the uncooled power turbine is 1500°F at intermediate rated power, SLS, standard day. The general mechanical features include tip shrouded turbine blades and segmented nozzles. Simplification, reduced number of parts and material substitutions have been introduced where trade-off studies indicated payoffs in cost, maintainability, life and engine weight.

TURBINES

- TRADE-OFF STUDIES OF VARIOUS GAS GENERATOR TURBINE BLADE COOLING SCHEMES RESULTED IN SELECTION OF THE SIMPLE RADIAL CONVECTION SYSTEM WHICH WAS USED IN THE GE12 DEMONSTRATOR ENGINE.

- TRADE-OFF STUDIES ON VARIOUS POWER TURBINE DESIGNS RESULTED IN 2 STAGE TIP SHROUDED DESIGN WITH SEGMENTED NOZZLES.

Bearings and Lube System

During the initial design studies for the ATE (GE12) Demonstrator, numerous rotor mounting configurations were evaluated by computer simulation programs such as VAST to determine the optimum number and location of bearings for the GE12 gas turbine engine.

After reviewing all the various combinations for rotor dynamic stability, ease of assembly and predicted durability the six bearing configuration (2 on the gas generator and four on the power turbine) was selected as providing the optimum combination of these characteristics.

BEARINGS AND LUBE SYSTEM

- TRADE-OFF STUDIES CONDUCTED ON VARIOUS BEARING/SUPPORT SYSTEM CONFIGURATIONS.

- SIX (6) BEARING LAYOUT INCORPORATING TWO (2) GAS GENERATOR BEARINGS AND FOUR (4) ON THE POWER TURBINE PROVIDED OPTIMUM COMBINATION OF ROTOR DYNAMICS, EASE OF ASSEMBLY AND PREDICTED DURABILITY.

GE12 to T700

One of the greatest examples where R&M requirements drove the design of the T700 engine occurred very early in the program near the end of the ATE (GE12) Demonstrator Program. There were no Maintainability Demonstrations funded/required in the ATE Program and U.S. Army AVSCOM decided to fund General Electric with a small supplemental Contract Mod to the basic ATE contract (Mod, #T00015) for the purpose of performing a Maintainability Demonstration/Reliability Analysis on the GE12 to gain experience/confidence that the maintainability requirements being specified in the RFO for the UTTAS Gas Turbine Engine could be achieved and that necessary changes to the engine configuration could be made before the engine design was finalized.

GE12 EVOLUTION TO T700

- SUPPLEMENTAL CONTRACT AWARDED BY U.S. ARMY NEAR END OF ATE PROGRAM TO PERFORM MAINTAINABILITY DEMO/ RELIABILITY ANALYSIS ON GE12 DEMONSTRATOR ENGINE.
- THIS WORK POINTED UP SEVERAL AREAS WHERE MAINTAINABILITY IMPROVEMENTS WERE REQUIRED IN THE GE12 DESIGN.

The ATE Maintainability demonstration was valuable for many reasons, and one of the most important was the verification of analysis techniques. A task analysis methhodology, including a set of standards, developed on other engine programs was applied to the GE12 drawings prior to the ATE demonstration, to determine expected task times. The actual demonstration effort along with the practice sessions were utilized to tune the standards so that, as a result, there was a known confidence level in the Maintainability task analysis process.

During the GE12 (ATE) demonstration in early May 1971, for example, it required 111.3 man-minutes (mm) to remove and replace (R/R) the fuel control, and 434 mm plus numerous hand tools and several special tools to R/R the combustion liner. These requirements were demonstrated with Army mechanics--June 1976--8 mm and 96 mm, respectively, with no special tools on the T700 engine which was completely redesigned to address the identified Qualitative and Quantitative problems. This redesign effort involved several iterations, maintained the integrity of the gas path, created a 4-module engine, put the accessory module on top for better access, and elimnated the need for any special tools at any field level. This then represented the proposed design for UTTAS, designated the T700-GE-700 engine. This design greatly simplified the external configuration by increased internal porting in frames and castings and addressed every problem/concern identified by the ATE "M" demonstration team.

The design was directed at minimizing required inspections and maintenance without sacrificing mechanical integrity and performance. The "module" concept was adopted to allow replacement of entire subsystems with a mimimum of time and mechanical expertise. The assembly and disassembly of modules was simplified for easier, quicker and more error-free maintenance.

ATE DEMONSTRATOR CONTRIBUTIONS

- PROVIDED A VEHICLE TO TRY OUT MAINTAINABILITY TASK ANALYSIS PROCESS.
- PROVIDED A DEMONSTRATION OF VARIOUS MAINTENANCE TASKS WHICH FLAGGED NEEDED IMPROVEMENTS.

Various other T700 maintenance features exemplify maintenance time, human factors and logistic improvements which can be achieved when discipline is imposed during engine design. For example: the number of different nuts and bolts requiring removal at organizational maintenance level was reduced from about 43 in earlier designs to 12 in the T700.

Tool requirements were also reduced. Field maintenance can be accomplished with only 10 common tools (Reference Page IIC-109) versus the 150 line-item tools available in the Army Aviation Mechanics Tool Kit "A07". No special tools are required at this maintenance level.

Innovative approaches in the design also reduce maintenance time and reduce the possibility for error. External plumbing has been extensively reduced by internal routing of lube and air lines and items requiring frequent service (filters, fuel control, etc.) are grouped on the accessory module.

Some traditional attachment methods were scrapped in favor of simplified approaches to save time and prevent errors. Electrical harnesses use self-locking electrical connectors with many lines and leads dressed along the engine with "*snap-in/snap-out*" brackets. Lockwire has also been eliminated in favor of self-locking nuts. The sum of many small time savings on the T700 is a very large reduction in maintenance time and effort with improved maintenance quality.

All of the above design trade-offs have been fully documented in T700 design books and other engineering documentation.

DESIGN ALTERNATIVE STUDIES SUMMARY

- DESIGN TRADE STUDIES HAVE BEEN USED EFFECTIVELY THROUGHOUT THE T700 DEVELOPMENT PROGRAM TO ACHIEVE R&M REQUIREMENTS.
- TRADE-OFF OR ALTERNATIVE DESIGN STUDIES DOCUMENTED IN ENGINEERING DESIGN BOOKS.
- THESE DESIGN TRADE-OFFS/ALTERNATIVE DESIGN STUDIES HAVE RESULTED IN NUMEROUS DESIGN CHANGES TO MEET R&M OBJECTIVES.

DESIGN EVALUATION ANALYSIS

DESIGN EVALUATION ANALYSIS

The RFQ for the 1500 SHP Turbine Engine for the UTTAS was very specific in the R&M attachments M5 and M6, respectively, in defining the requirement for ongoing/in-process Reliability and Maintainability Analyses during the design/development of the engine to be used as a tool for achieving the stated R&M requirements, not merely documenting the results of a design.

These requirements were delineated in the respective Reliability and Maintainability Program Plans and were executed as stated during the development of the T700 engine.

In the area of reliability, the Reliability Manager was responsible for providing the methods and procedures by which the responsible design personnel would perform the reliability analysis on his particular engine component. The reliability engineer was responsible for reviewing the results of the analysis and had the authority to approve or reject the results. Rejection required corrective action by the design engineer or review by higher management.

In the area of maintainability, the Maintainability Manager was responsible to see that each engine component design drawing was reviewed and signed-off by a maintainability engineer. He was also responsible for performing maintainability analyses on each engine component and transmitting the results of such analyses to the respective design engineering personnel for corrective action when required.

ANALYSIS SUMMARY

- R&M ANALYSES REQUIRED BY RFQ AND DELINEATED IN R&M PROGRAM PLANS.
- R&M ANALYSES WERE PERFORMED AS ONGOING/IN-PROCESS PROCEDURES IN CONJUNCTION WITH THE DESIGN PROCESS.
- R&M ANALYSES RESULTED IN SEVERAL DESIGN CHANGES--NOT JUST DOCUMENTATION OF FACT.
- R&M ANALYSES CONSIDERED VERY VALUABLE TOOL IN OBTAINING R&M OBJECTIVES.

RELIABILITY FEATURES

Reliability

Values for Mean Time Between Failures (MTBF) are normally determined from engine operation. Over 8,000 hours of T700-GE-700 development testing led to the completion of Qualification Test (QT), and resulted in an MTBF value of 1,272 hours for the QT design, as shown by the Bayesian Reliability Analysis Component Evaluation (BRACE). The PIDS requirements was for 1,200 hours MTBF at QT.

Since introduction into the field in April 1979, the engine has demonstrated operational reliability up to six times that of 1960 vintage engines which it is replacing in the U.S. Army inventory. Factors which contributed to this include: consolidation of functions and design simplicity attained by over one hundred reviews and by integration and monitoring of all engine development problems during the QT Program.

RELIABILITY OVERVIEW

- DEMONSTRATED MTBF AT COMPLETION OF MOT PROGRAM 1272 HOURS VS PIDS REQUIREMENT OF 1200.
- BASED ON FIRST QUARTER MILLION HOURS OF FIELD SERVICE, MTBF'S RUNNING SIX TIMES BETTER THAN 1960 VINTAGE ENGINES.
- THIS RESULT COMES ABOUT BY PAYING ATTENTION TO DETAILS ADDRESSING LESSONS LEARNED AND BY A JOINT TEAM EFFORT ON PART OF THE ARMY AND THE CONTRACTOR.

Reliability Features

A number of special design features, many of which are unique, have been introduced into the T700 design to give a marked increase in engine reliability when compared to previous engine designs. Some of the more significant features are:

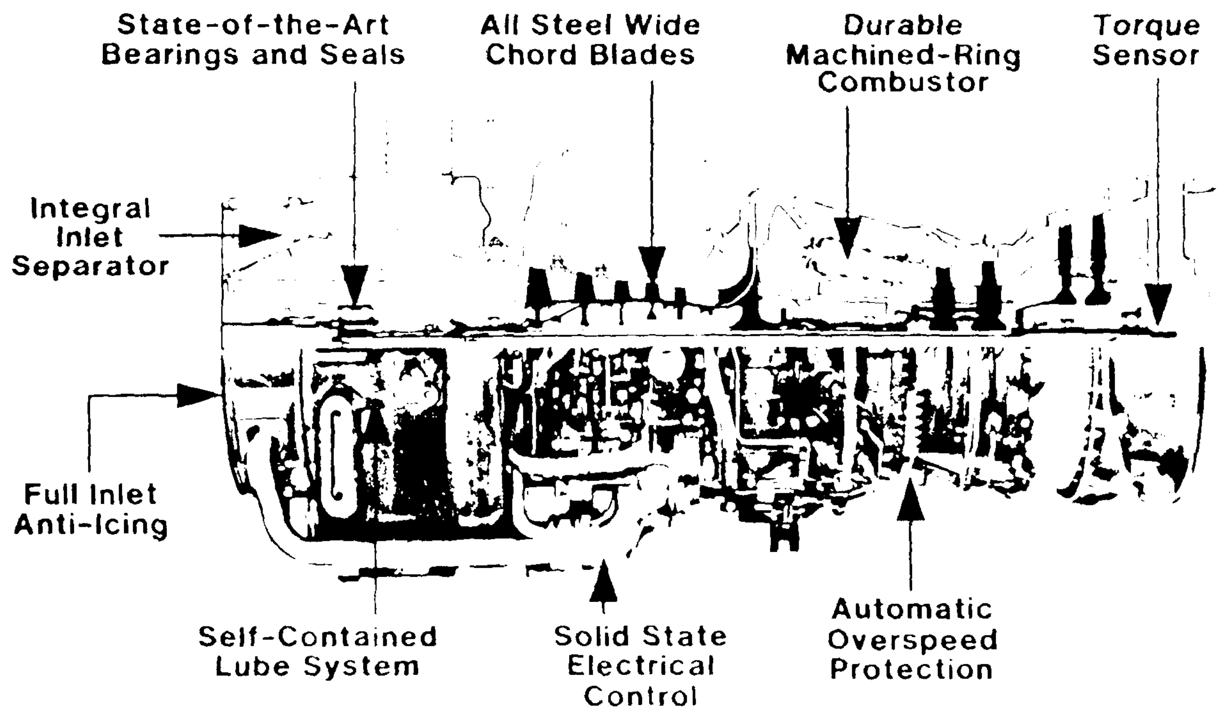
Compressor Assembly

1. Unitized blisk (integrated blade and disk) construction. Low-Cycle Fatigue (LCF) trouble areas, such as dovetails, have been eliminated.
2. Stage 3, 4 and 5 blisks beefed up for added strength.
3. Integral inlet particle separator with gear driven scavenging blower.
4. Variable geometry with compressor and control rigged to fixed stops, with fixed links.
5. Rugged torque shaft replacing bell cranks and actuator is integral with the HMU.
6. Stall margin has been increased by lengthening the Stage 1 compressor blades by 0.025 inch and by aerodynamic redesign of the centrifugal impeller and diffuser.

Combustor

1. Through-flow annular type for durability and compactness.
2. Design for 5,000-hour life.
3. Casing made from INCO 718 for strength and corrosion resistance.
4. Machined liner, giving low stress concentration and less susceptibility to cracking.

T700 Reliability Features



T700-710(120882)

Power Turbine

1. High strength shaft made from INCO 718.
2. Integral bucket tip shrouds provide vibration damping.
3. Design for 5,000-hour life.

Bearings and Lubrication

1. Bearings are made from M50 material with dual oil jets and positive locking of inner and outer races.
2. Size of No. 3 bearing was increased to provide longer life by YT design.
3. Roller bearings have oil squeeze film to dampen rotor vibration response.
4. No. 4 has trilobe design to prevent skidding.
5. Chip detector provides bearing monitoring with improved sensitivity.
6. Filter system has 3-micron element and impending bypass and bypass indicators. Capacity of filter was more than tripled (.6 sq-ft vs 1.895 sq-ft) to extend service life.
7. Lube system has a self-contained, integral tank and a special emergency oil system. Oil tank redesigned to improve level readability, reduce spillage and for ease of filling.

Control and Accessories and Fuel System

1. Consolidation of the fuel pump, fuel control and actuator into one package reduces potential leakage points, eliminates feedback cable and simplifies assembly.
2. Electrical connectors are hermetically sealed. Critical connectors have been made "scoop-proof" by extending the shells which prevents bending of the pins when [illegible].

AD-A143 104 T700 ENGINE CASE STUDY REPORT (IDA/OSD R&M (INSTITUTE FOR DEFENSE ANALYSE..(U) INSTITUTE FOR DEFENSE ANALYSES ALEXANDRIA VA P F GOREE AUG 83 IDA-D-22 3/4

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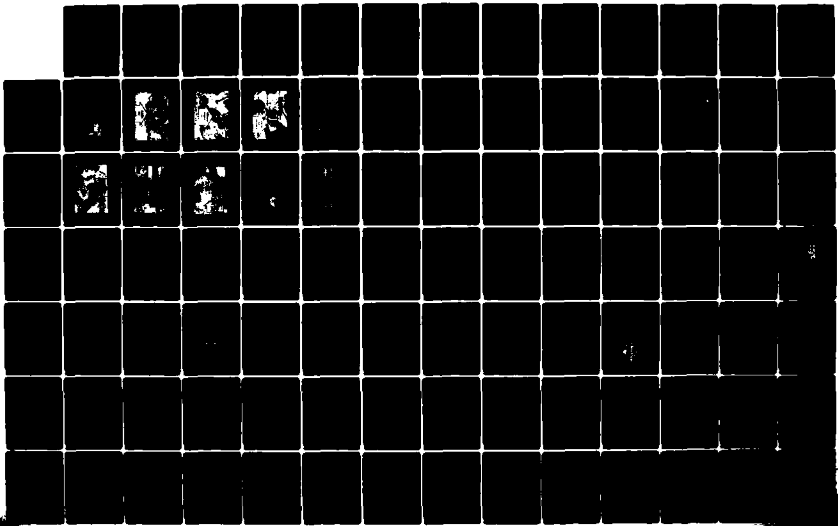

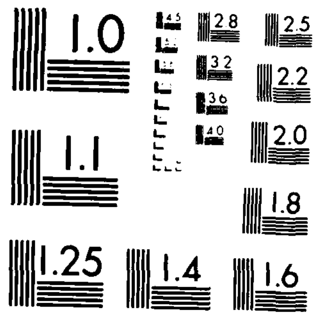

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

Control and Accessories and Fuel System (Continued)

3. Hydromechanical unit has torque motor with redundant windings.
4. Ignition exciter has redundant circuitry.
5. Ignition system has redundant igniters and power is engine-supplied.
6. System has seven 2-element probes to provide thermocouple redundancy and the immersion depth was changed for improved temperature measurement accuracy and control.

Configuration

1. Minimum use of external tubes and hoses.
2. Fuel and oil passages have been made integral with accessory gearbox, lube pump, hydromechanical unit, guide vane actuator, cooler and fuel pump.
3. Designed to misassembly and misconnection proof.
4. Design uses captive bolts eliminating the use of lockwire.

COMPUTER AIDED DESIGN

COMPUTER AIDED DESIGN

In 1972, when the contract was awarded for the design and development of the T700 engine, Computer Aided Design (CAD) methodology was just appearing on the scene and was not far enough along in 'the-state-of-the-art' to be utilized to the fullest potential in the initial design of the engine; however, computer programs were utilized in numerous ways in the design and R&M areas to assist the engineers in performing various analyses and design studies which contributed to the results of the engine in the areas of Reliability and Maintainability.

The following are some of the Computer programs which were used in the design of the T700 engine:

- Axial compressor airfoil generation including templates for manufacturing.
- Centrifugal compressor aerodynamic configuration.
- Turbine airfoil generation.
- Aeromechanical blade analyses.
- Heat transfer analysis.
- Rotor dynamics.
- Structures analyses.
- Control System/Airframe Rotor System Dynamic Simulation.
- Performance decks at various operational conditions.

During the course of the Development/Qualification Program, many computer aided design (CAD) tools have been put into place at the Lynn operation and gradually things like the clearance drawing for the engine have been computerized through the advanced Interactive graphics system so that stack-up checks may be performed when flow path changes are made to show the design engineer the impact of such changes on adjacent engine components.

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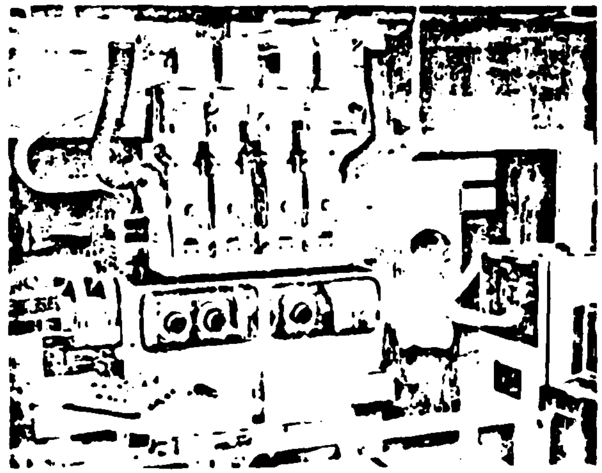
COMPUTER AIDED DESIGN

Computerized Production Facilities

Computer-Aided Design

- Advanced Interactive Graphics Systems

Five Axis/Four Spindle Miller



- One Piece T700 Compressor "Blisks" Automatically Machined from a Single Forging
- Four Units can be Machined Simultaneously

T700-1303(102280)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

During the development of the final MQT design for the Power Turbine, High Energy X-ray (HEX) pictures were taken on an actual operating T700 development engine at the General Electric outdoors testing facility at Peebles, Ohio. These X-Rays were used in conjunction with Interactive Graphics to establish the tip clearances and shroud configuration for the MQT design power turbine.

In the area of Reliability, a computer Math Model called "BRACE" was employed for assessing/predicting the Reliability Mean Time Between Failure (MTBF) for the T700 engine at any point in time. All failure data/corrective action experience was inputted to this program so that a current MTBF prediction was available at all times.

In a similar manner, a Maintainability Math Model (M^3) was employed which showed the relationships between components, parts and maintenance procedures and calculated qualitative maintainability values.

At the conclusion of the MQT Program and during the transition from development to production a Producibility Engineering Planning (PEP) program was put into place to 'productionize' the manufacture of the various components for the T700 engine. Much of the engine was programmed onto tapes for manufacture via numerical controlled machines (NCM) which resulted in greater part-to-part repeatability and tighter control of design tolerances.

USE OF COMPUTER IN T700 PROGRAM

- COMPUTER PROGRAMS USED EXTENSIVELY IN ALL PHASES OF DESIGN OF THE ENGINE.
- COMPUTER PROGRAMS UTILIZED TO TRACK/PREDICT ENGINE RELIABILITY.
- COMPUTER MATH MODEL UTILIZED FOR MAINTAINABILITY COMPARISONS
- T700 DESIGNS PROGRAMMED INTO INTERACTIVE GRAPHICS SYSTEM FOR USE IN CLEARANCE STACKS AND MASS PROPERTY STUDIES
- MUCH OF T700 ENGINE MANUFACTURED BY NUMERICAL CONTROLLED MACHINES (NCM).

ON-CONDITION MONITORING / DIAGNOSTICS

CONDITION MONITORING AND DIAGNOSTIC SYSTEM

On-Condition Maintenance

As a result of the demonstrated reliability of the engine, only a 10-hr inspection check, which is accomplished in three minutes, and a periodic inspection performed at 500 flight hour intervals (which can be performed on-wing in one hour), are required. On-condition monitoring coupled wi simplified LRU installation and rigging with no required adjustments contribute t overall mission readiness of the T700.

On-condition maintenance techni es are currently being utilized both in the factory and in the field. Of particular value has been the engine history recorder time-temperature integration to measure hot-part life used and for comparing the relative severity of field test engine operation with specification endurance test cycles. The engine chip detector has proven to be an effective means of detecting incipient oil-wetted part failures. Borescope inspection has also proven to be useful and easy to do both in the factory and on the wing. Ground use of the diagnostic connector for control troubleshooting has been effective, even though the currently available test box is only a non-powered resistance checker.

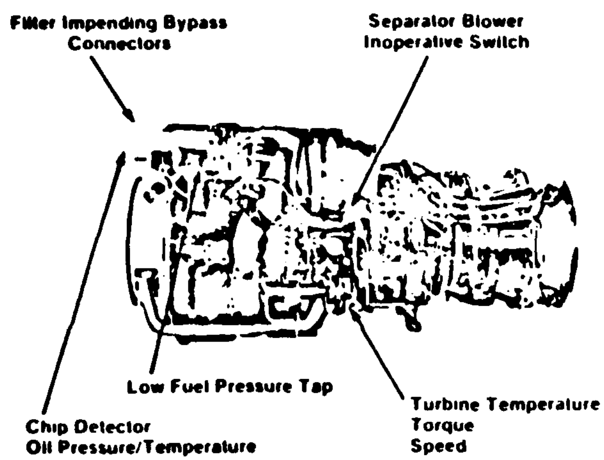
On-Condition Operation

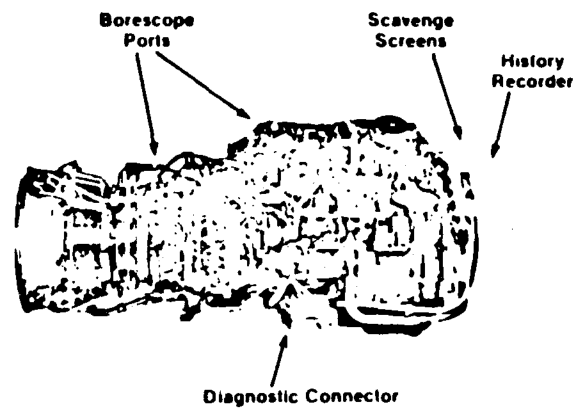
- **Utilizes Engine Status Monitors**
  - Engine History Recorder
  - Torque Reading
  - Turbine Temperature
  - Oil Level Gauges
  - Oil Pressure/Temperature
  - Filter Impending Bypass Indicators
  - Fuel Pressure
- **Enhanced by Fault Isolation Features**
  - Chip Detectors
  - Borescope Ports (7)
  - Filter Bypass Indicator

The development of condition monitoring equipment and procedures proceeded in parallel with the engine development to achieve an adequate data base for their effective field use. Features are:

1. Engine-mounted history recorder indicating number of LCF and LCF_2 (partial cycles) operating hours and an integrated time-temperature factor.
2. Engine magnetic chip detector.
3. Fuel and oil filter cockpit bypass indicators and popout button impeding bypass indicators.
4. Borescope capability: ports for inspection of compressor, combustor and IPS blower.
5. Electrical control diagnostic connector for fault isolation ground checks.

On-Condition Monitoring Provisions



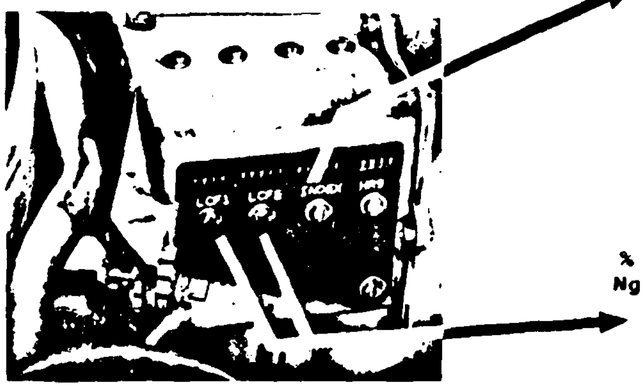


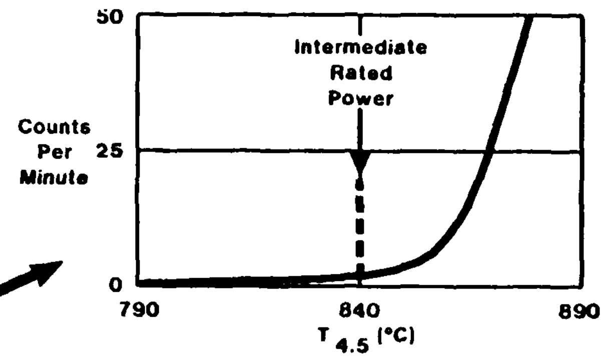
Cockpit-Monitored Diagnostics **Ground-Monitored Diagnostics**

Diagnostics Provisions Make On-Condition Operation Possible

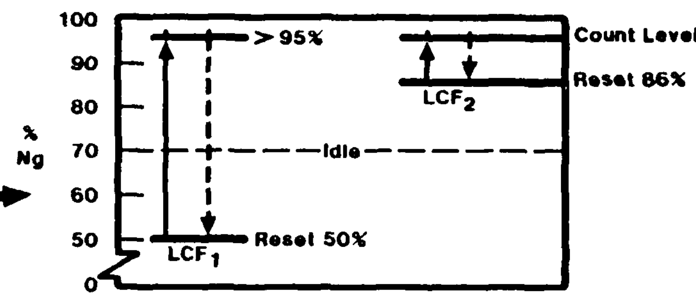
T700 History Recorder

- Integral With Engine
- Numerical Count Record
  - Total Run Time
  - Engine Life Consumed

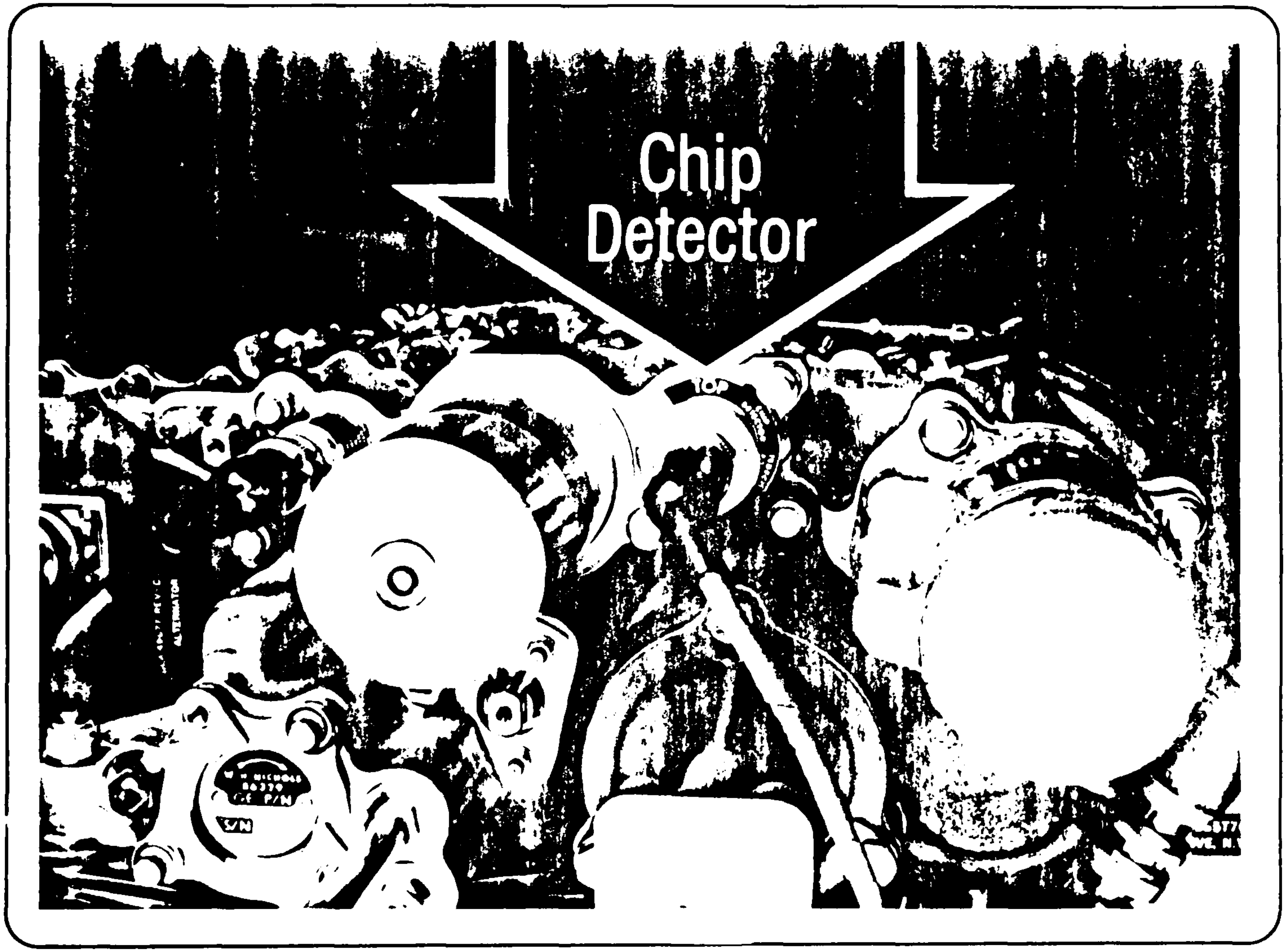




Time-Temperature Index



Low Cycle Fatigue Counters



T700-152(1-79)

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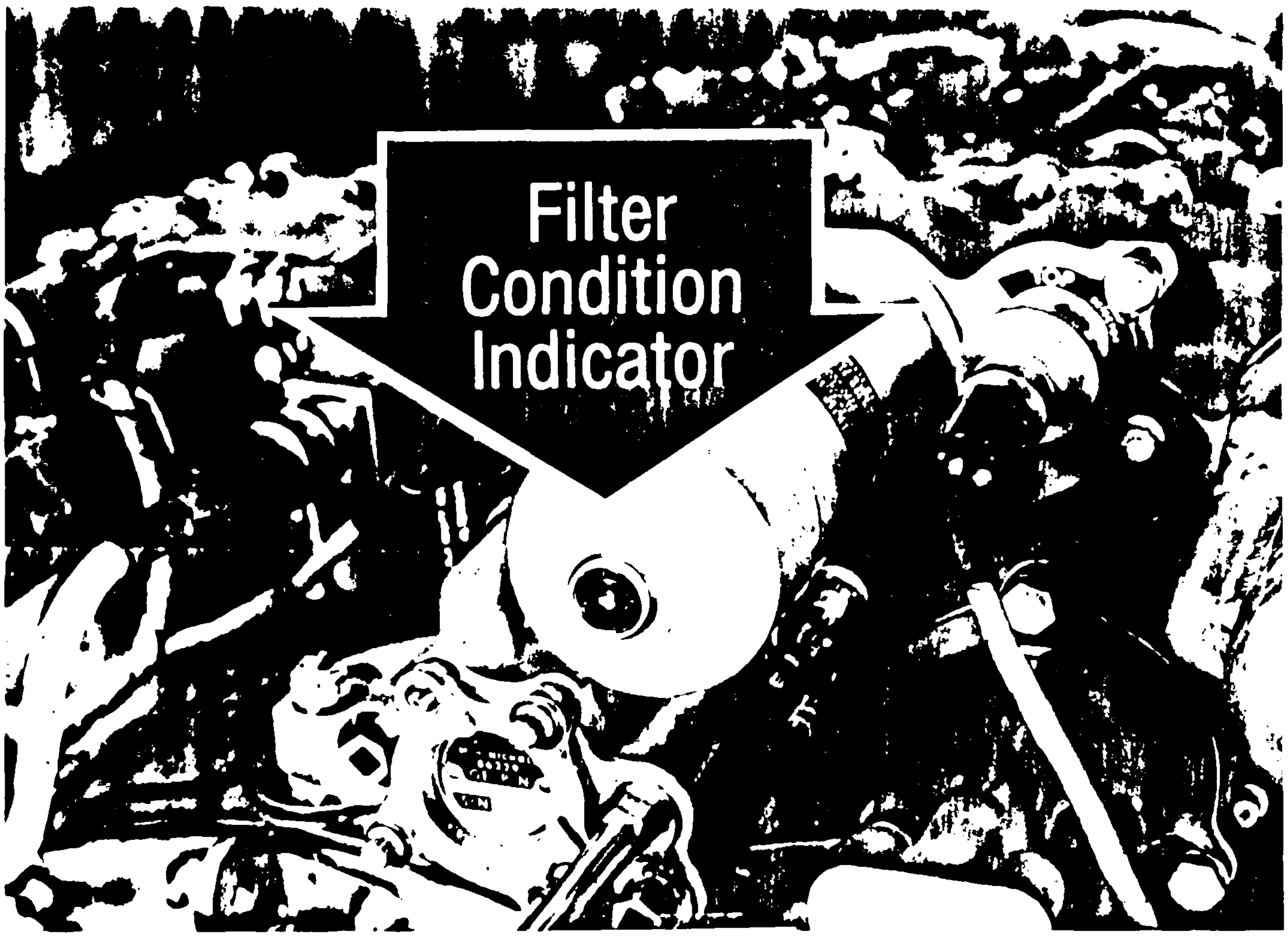

T700-151(1-79)

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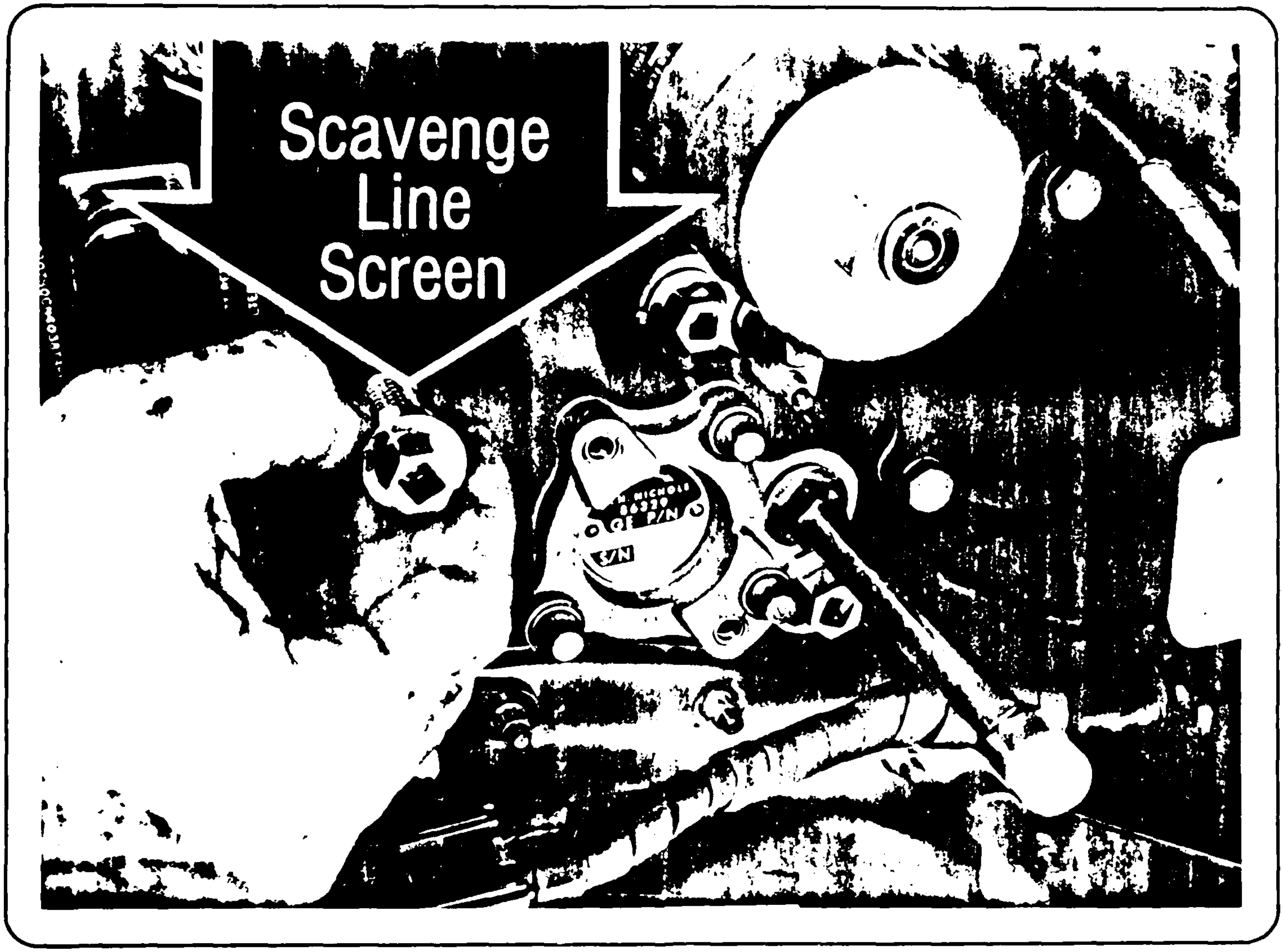


T700-153(1-79)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

Borescope Inspection On-Wing

On Condition Operation
Production Military Engines

- **Results**
  - No Time Between Overhaul (TBO)
  - Field Engines Operate "On Condition"
- **Contributing Factors**
  - Factory Durability Testing Which Leads Average Field Engine Age By More Than 4 Years
  - Fleet Leader Aircraft — Specific Mission . . . Get Engine Time Fast

FEATURES to FACILITATE MAINTENANCE

The following features were developed to address T700 maintainability. Some were contractually required and others were not. The T700 program was staffed with a versatile group of engineers headed by an aggressive manager, and supported by an experienced group of Maintainability engineers.

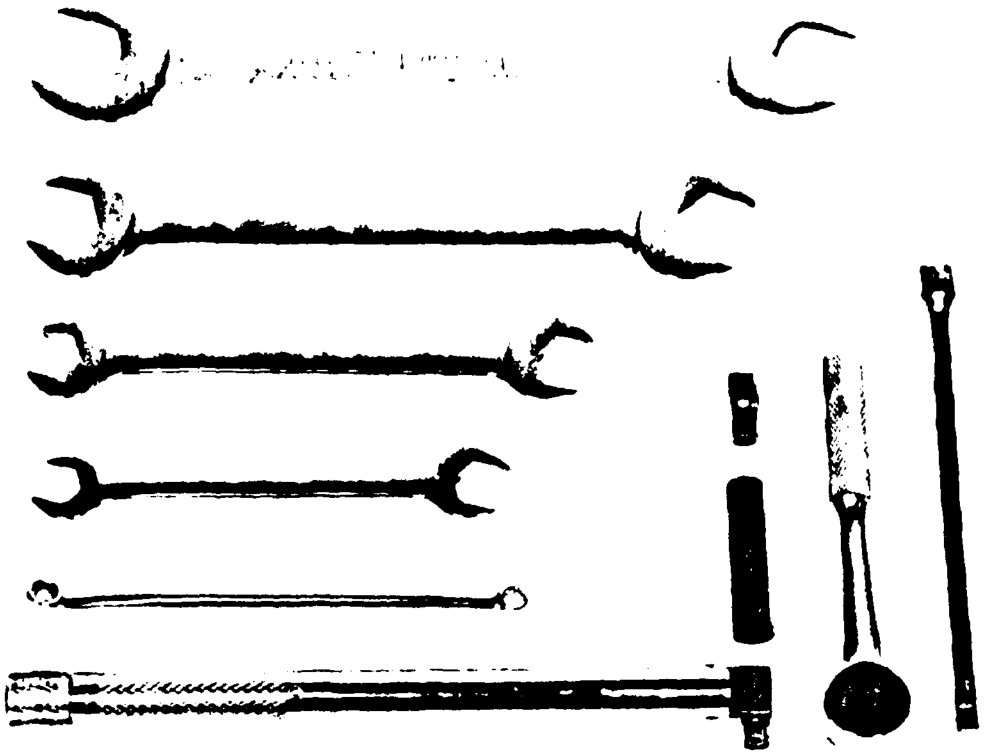
Features

- All Unit maintenance and module replacements require only 10 common hand tools.
- No special tools in the field.
- No field adjustments required.
- Self-aligning splines on LRU's not using V-band clamps.
- No critical dimension/calibration checks at field level (AVUM/AVIM).
- Oil level sight glasses - both sides.
- All LRU's replaceable without removing other engine components.
- Borescope provisions for on-condition maintenance.
- Completely interchangeable modules - no exposed sumps - no balance weights to R/R.
- Decals or permanent markings are utilized where practical to assist maintenance personnel.
- Nameplates oriented and lettered for installed readability.
- Impending bypass buttons on fuel and oil filters - filters R/R by hand.
- Lube pressure, temperature, fuel filter bypass, fuel lines, cables, positioned for simplicity and to avoid handling damage.
- Single size captive bolts on most Line Replaceable Units (LRU).
- Integral water wash manifold.
- No lockwire.
- Top-mounted accessory module.

- Modules removable without disturbing engine mounts.
- Scoop-proof - self-locking electrical connectors.
- Color-coded electrical cables.
- LRU's replaceable by single mechanic.
- No brackets or clamps on module interface flange.
- "Broom-stick" electrical cable clamps.
- Single-side wrenching in limited access areas.
- Minimum fastener sizes.
- New longer wrench pad nut for higher breakaway torque and longer tool life.
- Individual oil scavenge port screens for troubleshooting to correct sump.
- Fuel control also contains fuel pump and vane actuator - no feedback cable required.
- All fluid and electrical connections are Murphy-proof against interchange and wrench damage.
- Integral inlet separator for compressor protection against sand, dust and foreign objects.
- Engine-mount life counter for hours, time temperature factor and LCF counts.
- Master indicating magnetic chip detector.

- Radiographic inspection capability.
- Self-retained gask-o-seals.
- A repeatable wrench-arch method developed for fluid fittings.
- Inserts and studs have repair capability.

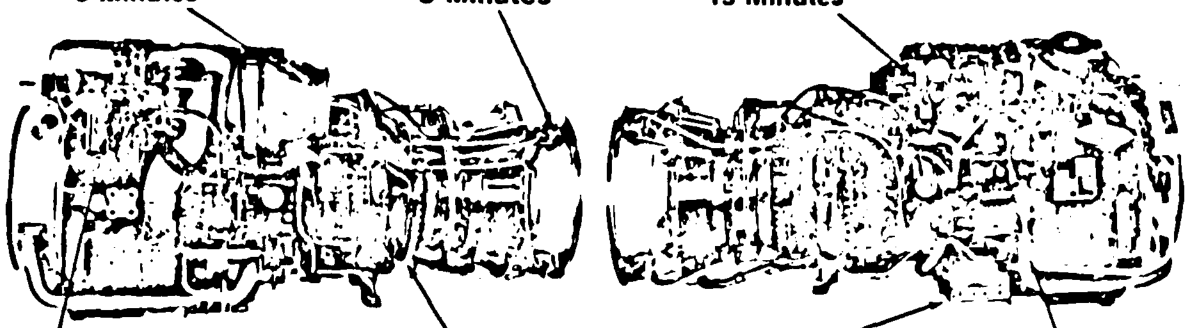
Only Tools Required at Field Level



T700-252(033081)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

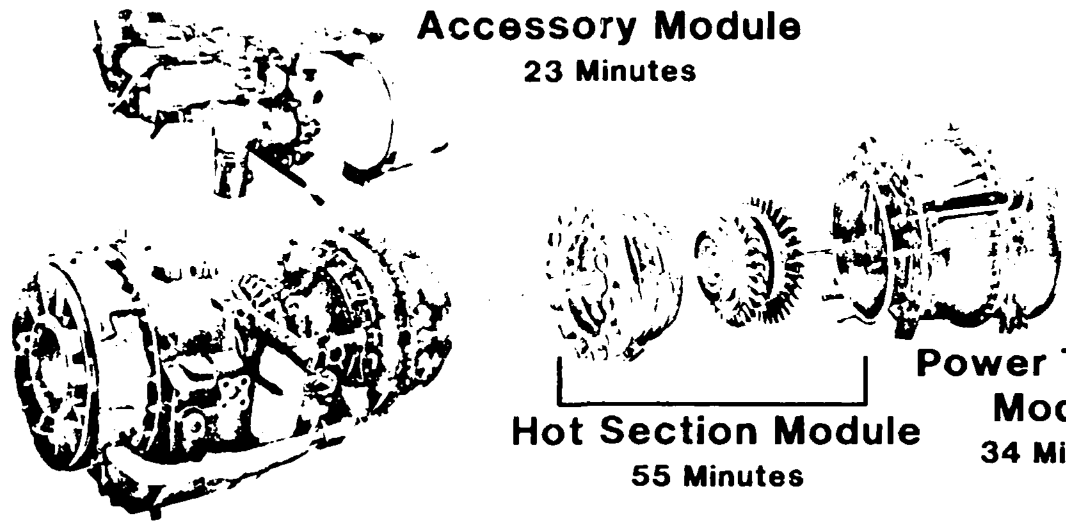
Flight Line Maintainability



- Demonstrated — June 1976 by U.S. Army Maintenance Team
- 1 Man, Elapsed Time

Remove and Replace — Ready to Run

Modular Maintainability



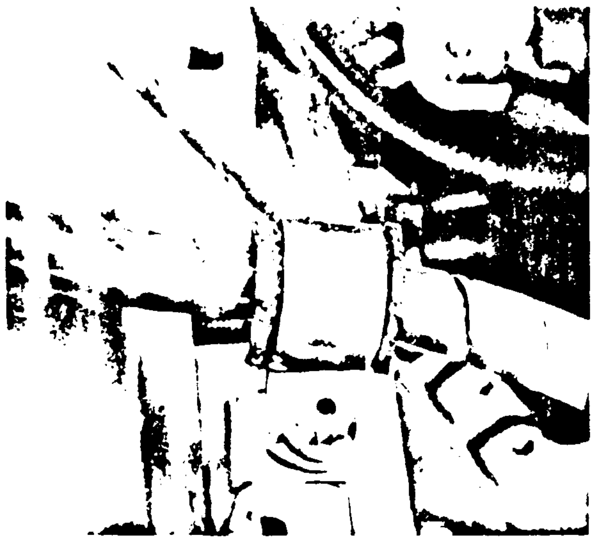
- Demonstrated by U.S. Army Maintenance Team
- Two Men, Elapsed Time

Remove and Replace — Ready to Run

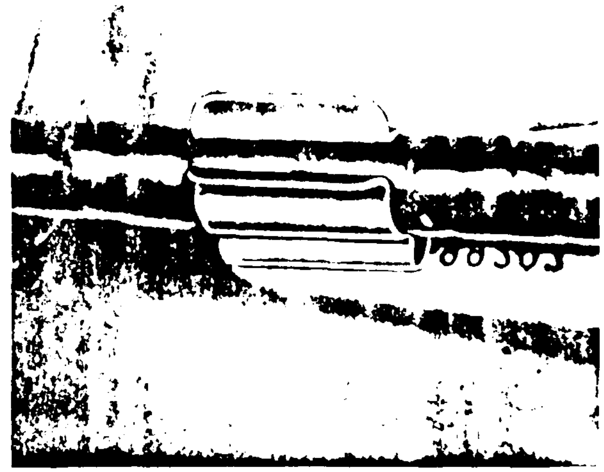
T700-242(032382)

Maintenance Simplification

Simplified Connector Brackets



Before

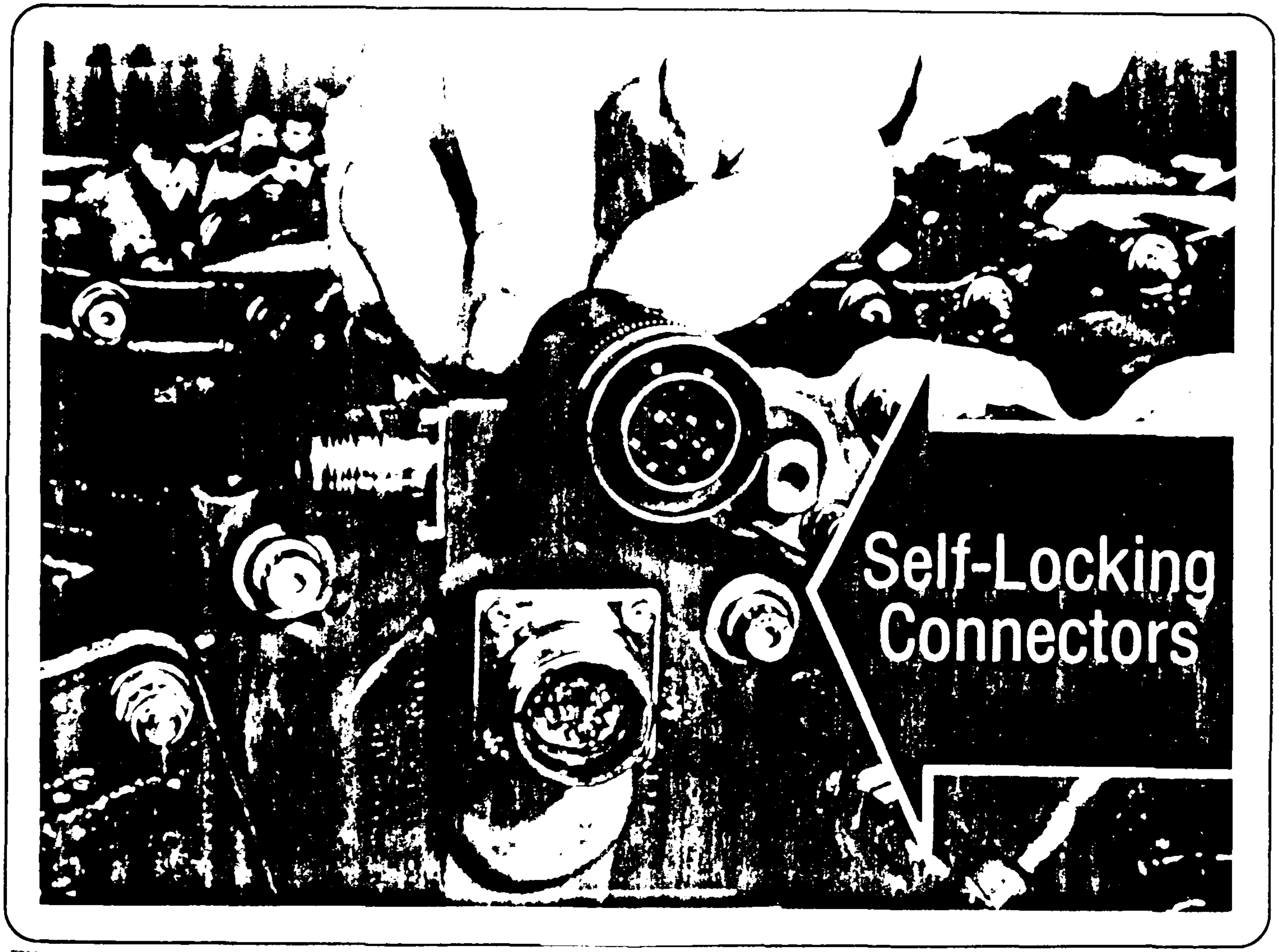


After

T700-158(11-78)

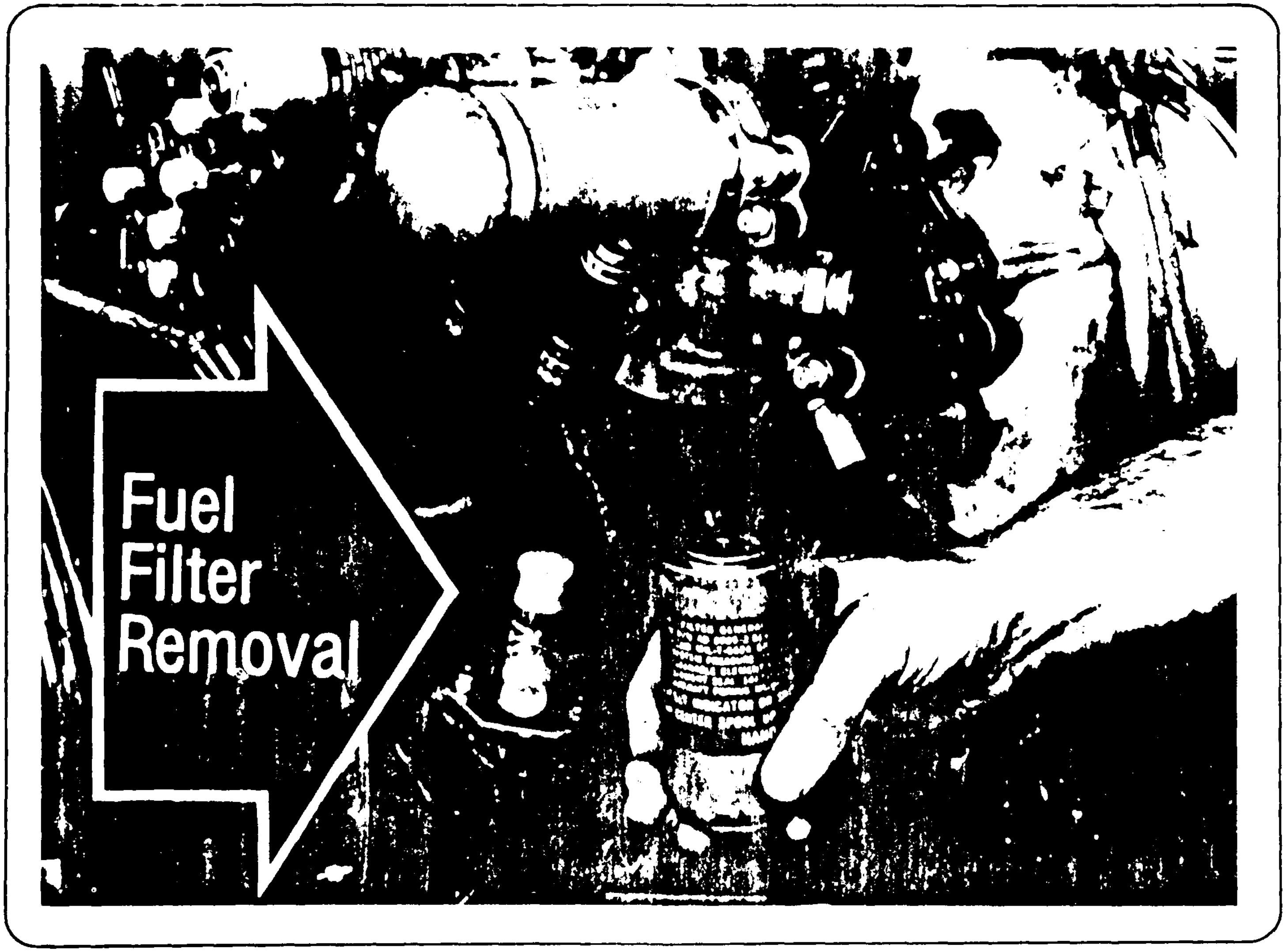
T700-157(1-79)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP



T700-159(1-79)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP



T700-156(1-79)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

Everything Needed is in Box

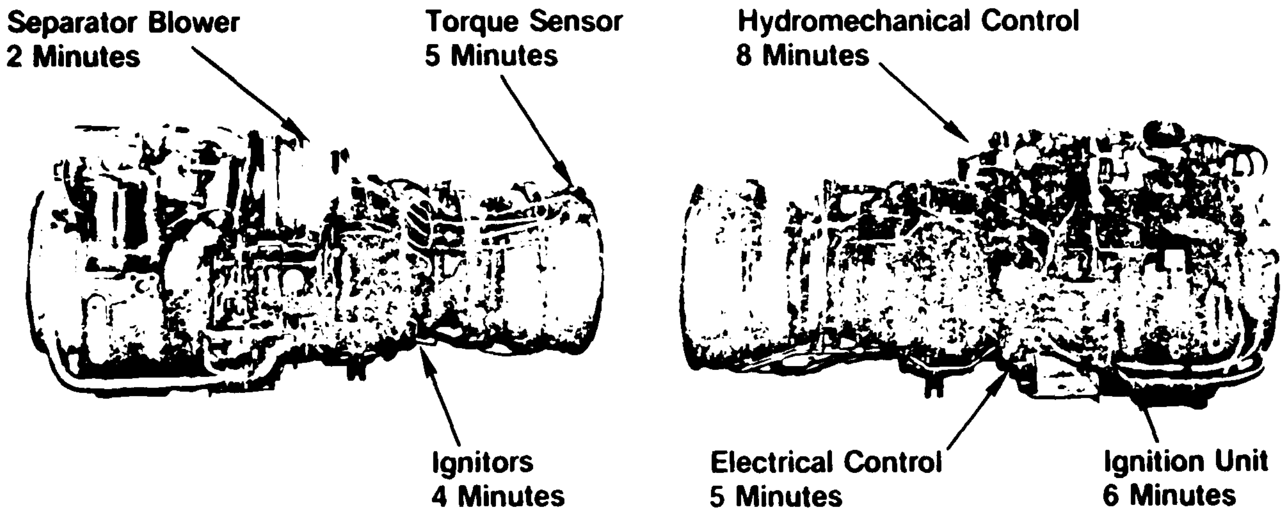
- All Attaching Parts Installed
- Instructions for that Part
- All Consumables

- No Rigging
- No Safety Wire
- No Adjustments
  - Part
  - Engine

T700-789(6-77)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

Designed for Easy Maintenance



- Snap-In Line Retainers
- Foolproof Electrical Connectors
- Color-Coded Wiring Harnesses
- Chip Detectors
- No Field Adjustments
- Filter Condition Indicator

60% of Unscheduled Field Maintenance Involves External Accessories

T700-1367 (032081)

GENERAL ELECTRIC COMPANY
AIRCHAFT ENGINE GROUP

MAINTENANCE PLAN

Maintenance

The T700 engine design was directed at minimizing required inspection and maintenance without sacrificing mechanical integrity and performance. Maintenance tasks were simplified for easier, quicker and more error-free maintenance. This simplified maintenance also reduced the need for highly specialized and trained maintenance personnel.

Corrective maintenance is performed on an on-condition basis. That is, the engine has no scheduled overhaul or parts replacement. Corrective maintenance is performed if there is a part failure or inspection indicating that parts require replacement. Preventive maintenance consists of a 10-hr inspection and a periodic inspection every 500 flight hours.

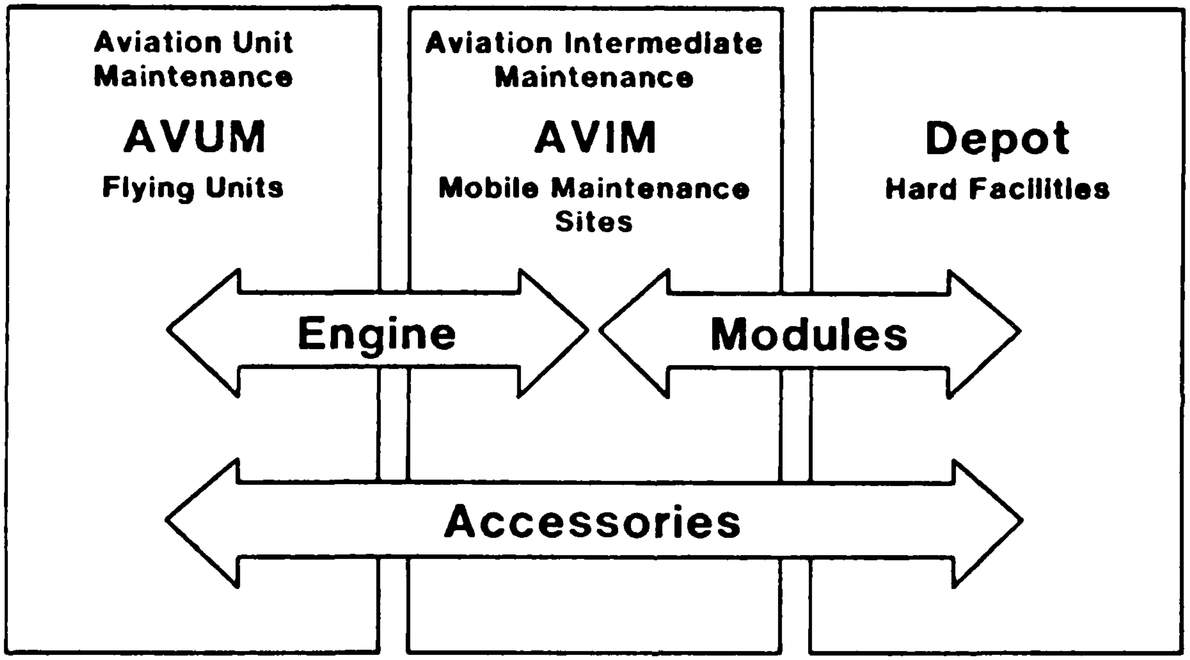
The module concept allows replacement of entire subsystems with a minimum of time. The engine consists of four modules: the accessory module, the cold section module, the hot section module, and the power turbine module. A module with a malfunction can be replaced using only ten common tools.

The three levels of Army Maintenance, Aviation Unit Maintenance (AVUM), Aviation Intermediate Maintenance (AVIM), and Depot, perform all T-700-GE-700 engine maintenance. AVUM removes and installs all Line Replaceable Units (LRU) with the engine installed. AVUM also performs the preventive maintenance 10-hr and period inspections. The 10-hr inspection consists of visual inspection of the engine, checking fuel and lube filter impending bypass indicators, checking history recorder, and checking engine oil level. The period inspection includes a detailed borescope inspection, a detailed engine visual inspection and the 10-hr inspection tasks. AVIM replaces modules and performs limited parts replacement on the modules. The Depot performs complete module disassembly and assembly and repairs all components.

Three-Level Maintenance

- **AVUM (Unit)**
  - Installed in Aircraft
  - External and Remove/Replace Tasks
- **AVIM (Intermediate)**
  - Uninstalled
  - Remove/Replace Modules
  - Remove/Replace LRU's
- **Depot**
  - Complete Disassembly/Repair
    - Engine
    - Components

3 Level Maintenance and Modular Repair



T700 Maintenance Concept Summary

- Simplified Field Maintenance
- No Special Tools
- Minimum Special Test Equipment
- Modular Maintainability
- On-Condition Operation
- Flexible 3-Level or 2-Level Maintenance System

Reduced Cost of Ownership

T700 Maintenance Concept Summary

- Simplified Field Maintenance
- No Special Tools
- Minimum Special Test Equipment
- Modular Maintainability
- On-Condition Operation
- Flexible 3-Level or 2-Level Maintenance System

Reduced Cost of Ownership

MANUFACTURING

MANUFACTURING

Included in the full scale development contract for the T700 engine was an order for 18 XT700 engines and 56 YT700 engines to support the UTTAS Flight Test Program. As a result of the timing, long lead time materials had to be released with the first block of development engines and detail parts orders were also released at the same time development hardware was released.

This was the first time that such a significant number of XT/YT engines had ever been ordered to be built and delivered simultaneously with the Development/Qualification program and thus very close integration between the Project Design, Logistics Functions and Manufacturing was required so that any early development problems could expeditiously be addressed and changes factored into the ST/YT engines in manufacture.

By the same token, this 'mini' production order provided Manufacturing with a very early experience base which could be used later in transitioning to full production.

Each XT and YT engine went through an initial acceptance test referred to as a "green-run'. This green-run was followed by a partial disassembly/inspection/rebuild culminating in a 'final' run prior to shipment to the respective AVM.

These post green-run inspections provided design engineers with information at a very early stage in the engine development program to evaluate such criteria as:

- Rub patterns/break-in procedures
- Leakage paths
- Clearances
- Vibration Characteristics
- Lube consumption/leakage
- Assembly procedures
- Torques
- Maintainability problems

The design engineers and reliability engineers worked closely with production engineering on a daily basis. Numerous design reviews were conducted to review problems experienced during XT/YT manufacture/production and the lessons learned were factored into the Development/Qualification Program.

MANUFACTURING SUMMARY

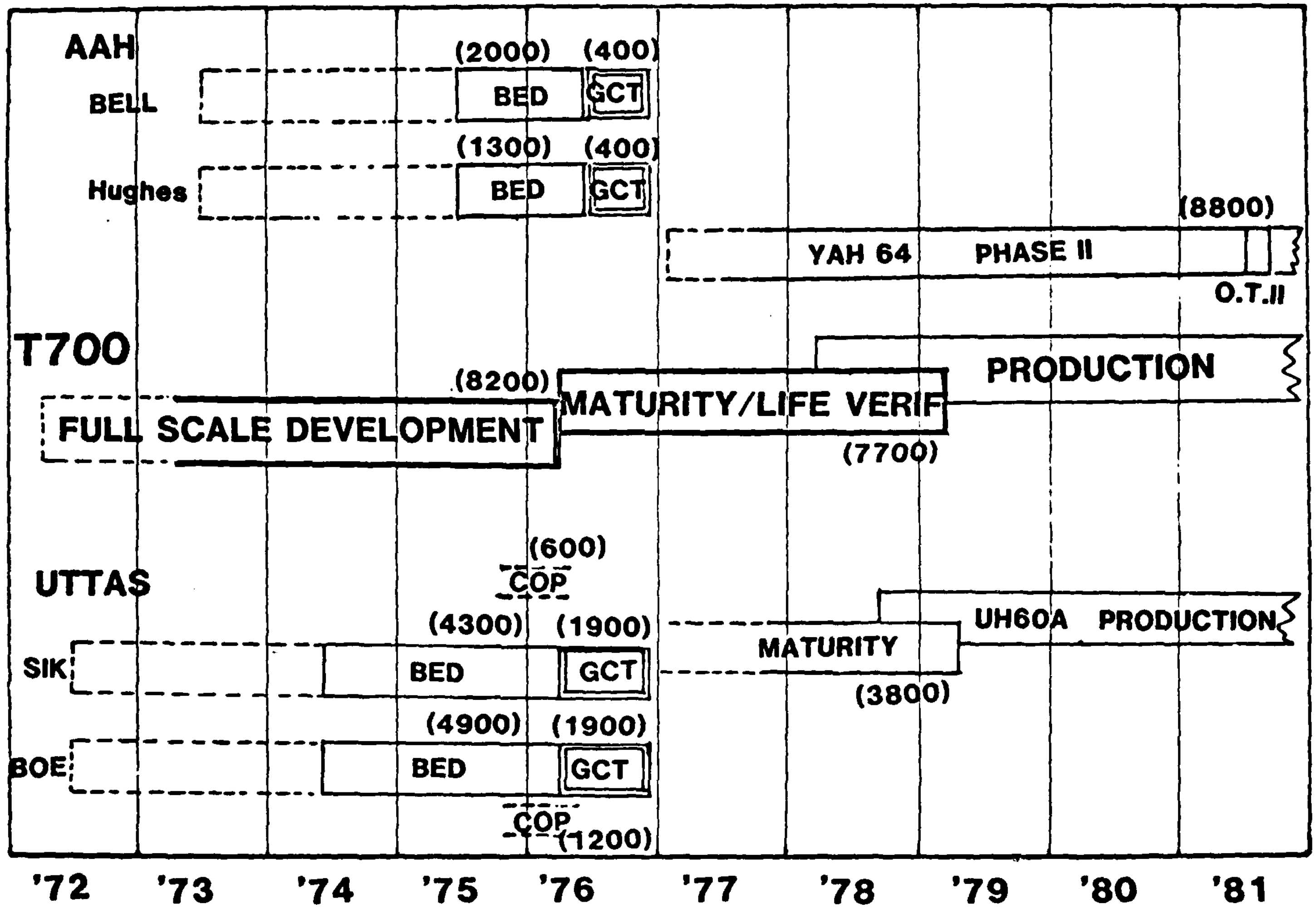
- SIMULTANEOUS XT/YT 'MINI' PRODUCTION ORDER PROVIDED VALUABLE INFORMATION TO DESIGN/MAINTAINABILITY ENGINEERS FOR EARLY PROBLEM RECOGNITION/CORRECTIVE ACTION.
- MINI-PRODUCTION ORDER OF XT/YT ENGINES PROVIDED MANUFACTURING WITH VALUABLE INFORMATION USED TO MAKE SMOOTH TRANSITION FROM 'SOFT' TOOLING TO PRODUCTION TOOLING.

TEST and EVALUATION

DESIGN LIMIT QUALIFICATION TESTING

The U.S. Army awarded the General Electric Company a contract in March, 1972, for the full scale development and qualification of the T700-GE-700 gas turbine engine to power the new Army UTTAS helicopter. This contract was unique in that it also included and Air Vehicle Support Program which was to be conducted in parallel with the T700 Engine Development/Qualification Program. In late 1971, the U.S. Army had issued an RFP to the helicopter industry for the design and development of a new Utility Tactical Transport Aircraft System (UTTAS). In mid-1972, Sikorsky Aircraft Division and Boeing Vertol Company were selected to each build three (3) production prototype flight aircraft and one ground test vehicle (GTV). Both competitive models would be powered by the U.S. Army developed T700 turboshaft engine.

T700/BLACK HAWK/APACHE DEVELOPMENT PROGRAM

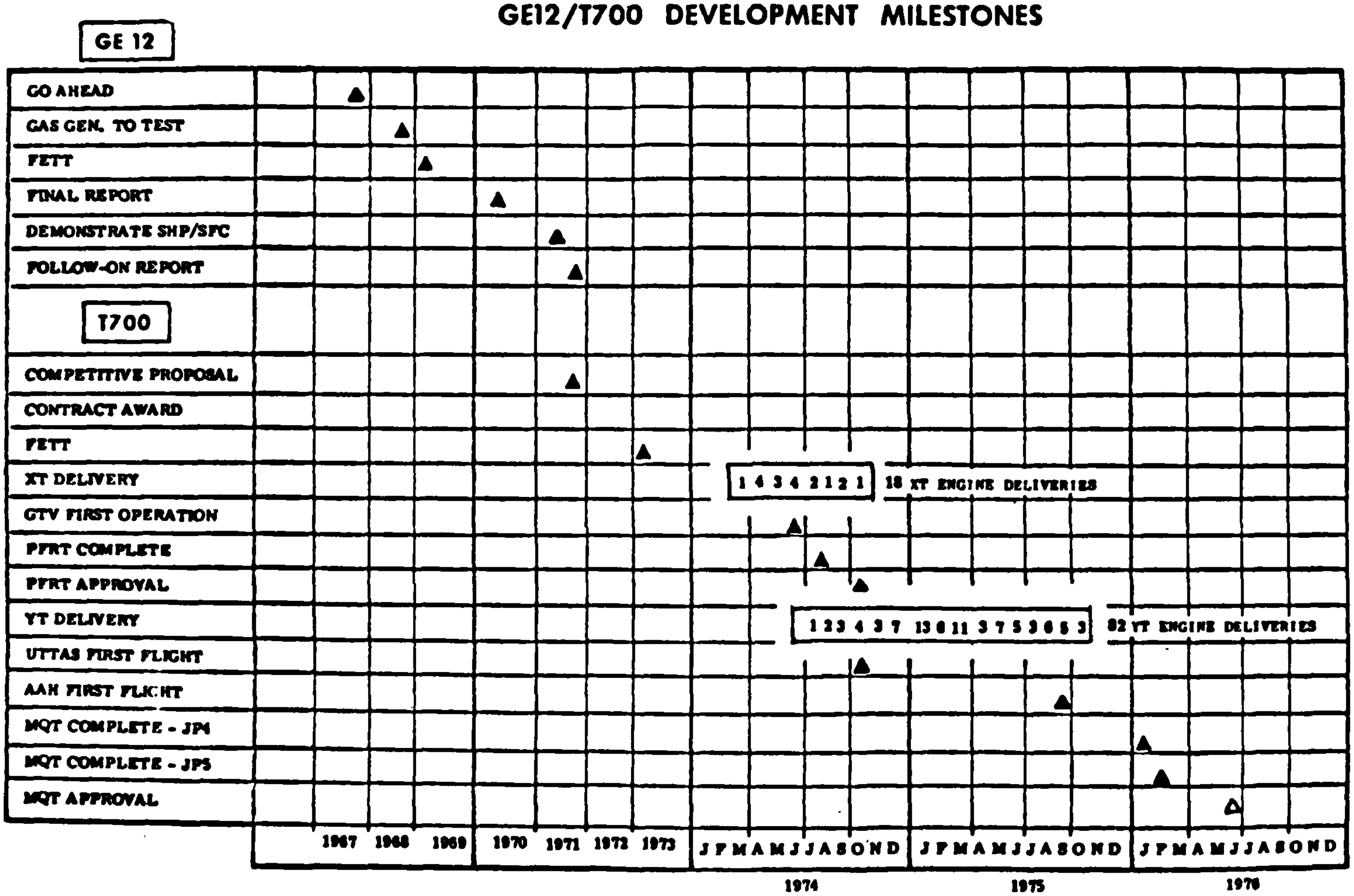


Less than one year later, the first T700-GE-700 development engine went to the test cell on 27 February 1983. This was the start of the full scale development/qualification program on the T700 engine which was completed three (3) years later with the successful qualification of the T700-GE-700 turboshaft engine in March, 1976. During this development/qualification program, fourteen (14) development T700 engines were utilized in addition to tests on several other XT and YT models and a total of 8200 development test hours were accumulated vs. the contractual minimum requirement of 7000 hours.

In parallel with the T700 engine development program, both UTTAS Airframe Vehicle Manufacturers (AVM's) Boeing and Sikorsky, built their first UTTAS flight test aircraft and the Sikorsky built YUH-60 made its first flight in September, 1974 with the first flight of the Boeing built YUH-61 taking place one month later in October, 1974. Both of these aircraft were powered by YT700 engines which had completed the official 60-hour Pre-Flight Rotating Test (PFRT) in August, 1974.

In late 1972, the U.S. Army issued an RFP for the design/development of a new Advanced Attack Helicopter (AAH). In mid-1973, the U.S. Army awarded development contracts to Bell Textron and Hughes Helicopter for a competitive fly-off program for the AAH and it was also to be powered by the new T700-GE-700 engines. The first AAH built by Hughes, YAH-64, flew in September, 1975. Thus, before the T700 qualification program was completed, four (4) different all-new helicopter models were being flown, all powered by T700-GE-700 engines.

GE12/T700 DEVELOPMENT MILESTONES



Page IIE-9 shows the detailed development test program showing the utilization of each of the fourteen (14) development engines.

Page IIE-10 is a summary of the official testing which was completed for the PFRT program. This cleared the YT700 engine for flight.

Page IIE-11 is a summary of the twenty (20) official engine qualification tests along with all of the official component tests that were completed to satisfy the requirements of the PIDS for official qualification of the T700-GE-700 engine.

During the T700 engine development/qualification as a fundamental element of the Army/GE campaign to enhance installed engine reliability, extensive attention was given to accelerated environmental testing in advance of any significant field test operation. This testing included:

- Salt - Although the T700 was developed under Army auspices, it completed a 150-hour Navy salt ingestion test at the Navy's facility at Trenton, NJ (in addition to the required Army salt corrosion test).

- Ice - Full engine anti-icing capability was also demonstrated at the Navy facility at Trenton, NJ. This included operation at -5°C with a liquid water content of 2 g/m^3. Ice ingestion testing showed engine capability to absorb up to a 2-inch ice ball traveling at 250 knots with little performance loss.

T700 DEVELOPMENT TEST PLAN

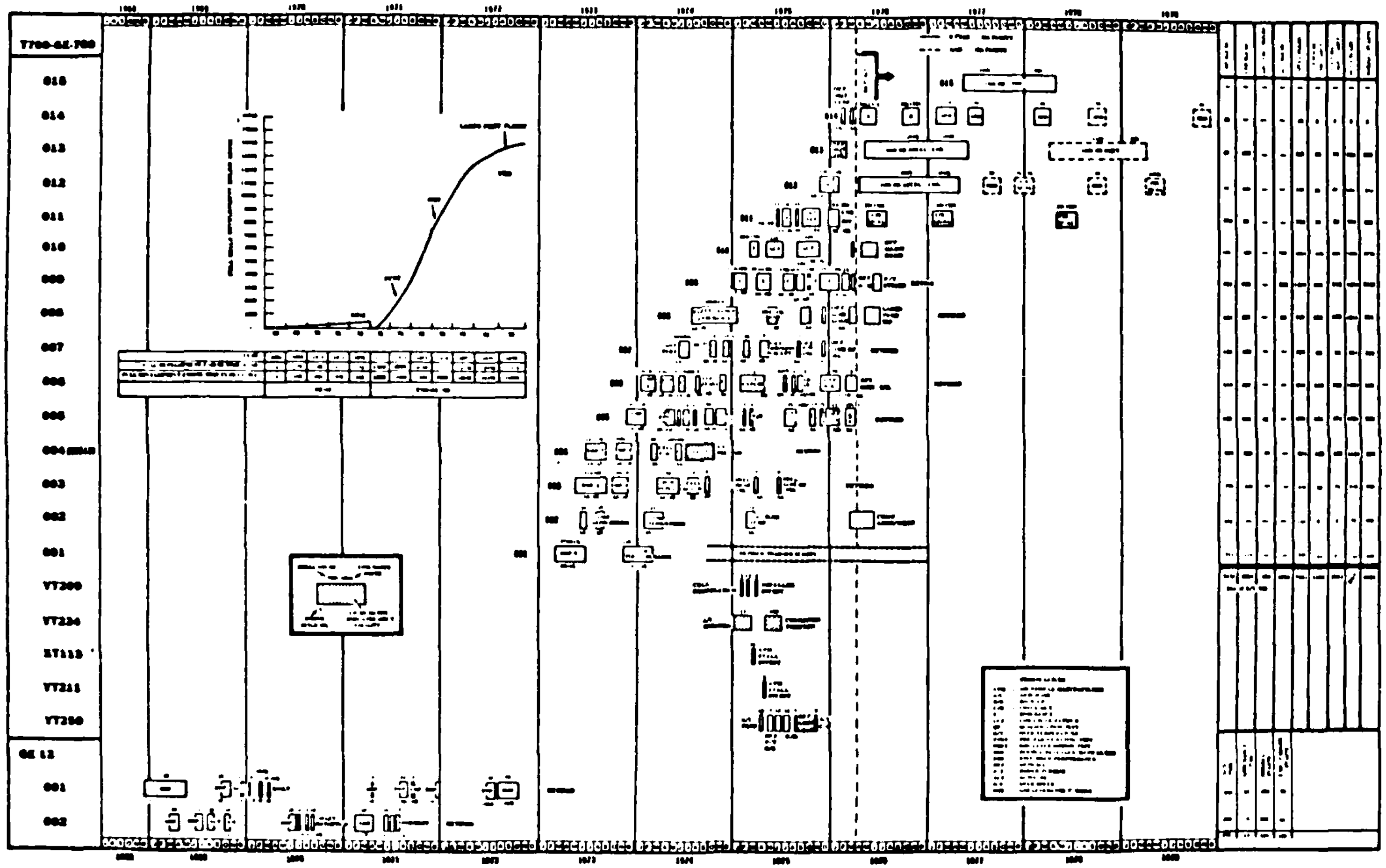


TABLE 2 - 3

1. T700-GE-700 Prime Item Development Specification AMC-CP-2222-02000A

Official PFRT Reports

Title	GE Report	Date
• Summary Report	R74AEG74	15 Nov. 1974
60-Hour Endurance Test	R74AEG57 Vol. 1	24 Aug. 1974
60-Hour Endurance Test Teardown Inspection	R74AEG57 Vol. 2	24 Aug. 1974
60-Hour Endurance Test Component Pre- and Post PFRT Calibration and Inspection Results	R74AEG57 Vol. 3	24 Aug. 1974
• Altitude Performance	R74AEG52	19 July 1974
• Electrical and Electronic Equipment Emission and Susceptibility Tests	R74AEG300	22 July 1974
• Engine Heat Rejection	R74AEG37	15 June 1974
• Compressor Bleed Air Analyses	TM74AFC1158	2 Oct. 1974
• Structural Analyses	R74AEG40	15 Aug. 1974
• Rotor Structural Integrity Analyses	R74AEG33	15 May 1974
• Anti-Icing and Starting Bleed Valve	R74AEG60	24 Aug. 1974
• Power Turbine Speed and Torque Sensor	R74AEG26	15 May 1974
• Fuel Boost Pump	R74AEG58	16 Aug. 1974
• Alternator, Ignition Exciter Ignition Leads, Igniters	R74AEG53	31 July 1974
• High Pressure Fuel Pump	R73AEG44	14 Dec. 1973
• Fuel and Lube Systems	R74AEG61	24 Aug. 1974
• Electrical Control Subsystem Simulated Operational Test	R74AEG354	23 July 1974
• Electrical Control Subsystem Explosion Proof Test	R74AEG355	24 July 1974
• Oil Tank Pressure Test	GE letter 1-MCH-215	30 Aug. 1974

3. T700-GE-700 Reliability Report — 20 Jan. 1975; 20 May 1975; 20 Sept 1975

4. T700-GE-700 Maintainability: Quarterly Progress Report — 20 Jan. 1975; 21 Apr. 1975; 21 July 1975; 20 Oct. 1975

5. Program Progress Review Meeting Report, Book I — 9 June 1975; 9 Oct. 1975

TABLE 2 - 4

OFFICIAL MODEL QUALIFICATION TESTS/REPORTS

	Description	Report	Date
1.	150 Hour Endurance Test - JP-4	R76AEG029	Test cpt.
2.	150 Hour Endurance Test - JP-5	R76AEG030	Test cpt.
3.	Altitude Performance Tests	R76AEG020	27 Feb. '76
4.	Engine Overtemperature Test	R75AEG024	15 Dec. '75
5.	Engine Overtemperature Control System Test	R75AEG029	31 Dec. '75
6.	Power Turbine Overspeed Test	R75AEG013	15 July '75
7.	Gas Generator Turbine Overspeed Test	R75AEG022	28 Nov. '75
8.	Engine Overspeed Control System Test	R75AEG025	28 Dec. '75
9.	Atmospheric Water Ingestion Test	R75AEG023	28 Nov. '75
10.	Cold and Hot Temperature Starting & Acceleration Tests	R76AEG016	Test cpt.
11.	Windmilling Test	R76AEG035	Test cpt.
12.	Anti-icing Test	R76AEG031	Test cpt.
13.	Ice Ingestion Test	R76AEG037	Test cpt.
14.	Bird Ingestion Test	R76AEG034	Test cpt.
15.	Low Cycle Thermal Fatigue Test	R76AEG028	31 Mar. '76
16.	Loss of Oil Test	R76AEG032	Test cpt.
17.	Attitude Test	R76AEG033	Test cpt.
18.	Smoke Emission Test	R76AEG001	30 Jan. '76
19.	Salt Corrosion Susceptibility Test	R75AEG012	1 Sept '75
20.	Sand Ingestion Test (Phase I & II)	R75AEG030	31 Dec. '75

COMPONENT TESTS/REPORTS

	Description	Report	Date
1.	Power Turbine Speed and Torque Sensor	R75AEG011	15 June '75
2.	Wiring Harnesses	R75AEG016	15 July '75
3.	Fuel Boost Pump	R76AEG002	30 Jan. '76
4.	HydroMechanical Unit, Sequence Valve, Fuel Filter, Primer Nozzles Simulated Operational Test & Environmental Test	R76AEG038	Test cpt.
5.	Fuel and Lube System Simulated Operational Test & Environmental Test	R76AEG039	Test cpt.
6.	Electrical Control Unit Simulated Operational Test	R75AEG027	31 Dec. '75
7.	Electrical Control Unit, History Recorder Environmental Test	R76AEG010	30 Jan. '76
8.	Alternator, Ignition Exciter, Ignition Leads	R75AEG017	15 Aug. '75
9.	Ignition Plugs	R76AEG003	30 Jan. '76
10.	Anti-Icing and Start Bleed Valve	R76AEG027	31 Mar. '76
11.	High Pressure Pump Simulated Operational Test	R76AEG040	Test cpt.
12.	Fuel System Performance Test	R76AEG041	Test cpt.
13.	History Recorder Simulated Operational Test	R76AEG026	31 Mar. '76

OTHER TESTS/REPORTS

	Description	Report	Date
1.	Containment Test	R75AEG001 Rev.	15 Dec. '75
2.	Wear Rate of Oil Wetted Parts	Letter	No test
3.	Maintainability Demonstration	-	June '76 Demo
4.	Fuel Control Reliability Analysis	Letter	No test
5.	Fuel System Calibration Limits	Letter	No test
6.	Rotor Structural Integrity Review	R76AEG042	No test
7.	Engine Design	R76AEG043	No test
8.	Vibration Survey	R76AEG008	16 Jan. '76

- Water - Water ingestion testing included both mist ingestion (up to 5% by volume) and instantaneous single slug ingestion (up to 450 cc).

- Hot/Cold - Temperature extremes from +55°C to -54°C were thoroughly evaluated for long term (10 hours) soaking effects, especially starting and mission cycle running.

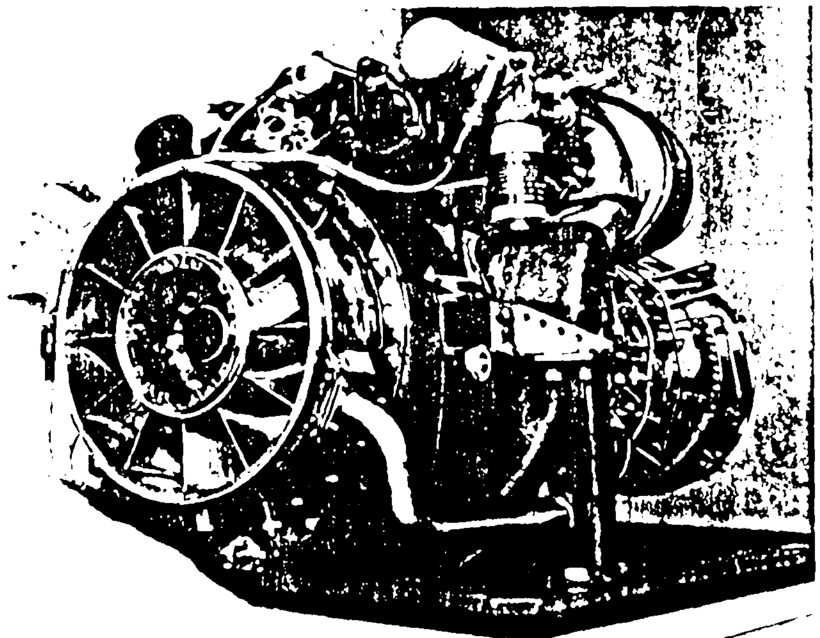
- Sand - The T700 ingested more than 72 lbs. of "C" spec sand (0-1000) in 50 hours of engine operation. This is equivalent to more than 3,000 helicopter take-offs and landings on a dry, sandy beach.

- Low Cycle Fatigue - More than 3500 thermal cycles on a single engine were demonstrated as part of the MOT Program. Each cycle included a transient power burst from ground idle to maximum power and back, followed by an engine shutdown every other cycle. This was part of the overall effort to verify the engine's capability to meet its 5,000-hour design life requirement prior to production.

- Bird - Two birds weighing 2.2 ounces each were ingested at more than 100 knots simulated flight speed with no subsequent performance deterioration.

Another major portion of the accelerated engine life test program was the extremely strenuous endurance cycle testing performed for both the 60-hour PFRT and the two 150-hour MOT's. The standard endurance cycle specified that most testing was to be conducted between maximum continuous and intermediate rated powers (Ref. pg. IIE-15). Translated into engine hot section life terms, this "fleet leader" concept defined 300 hours MOT testing to be equivalent to more than 3,000 hours of typical field operation. This ratio has been

Sand Ingestion Test



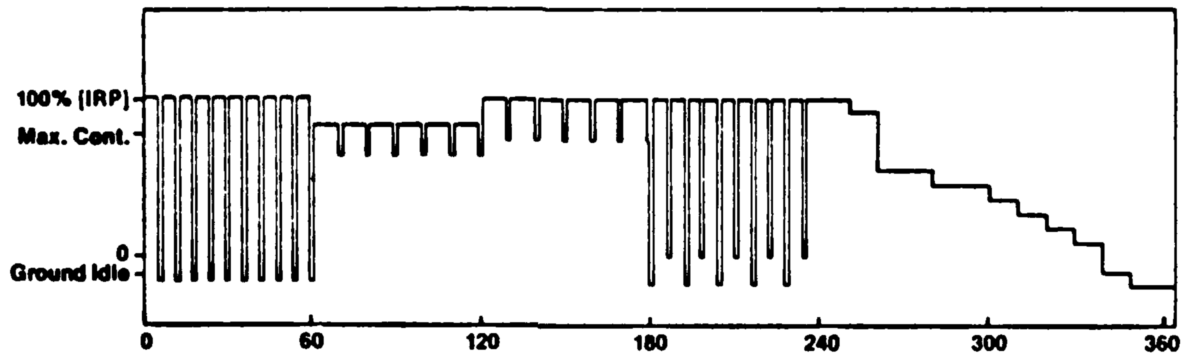
Simulated 3,000 Desert/Beach Takeoffs

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

Water Ingestion Capability

- 5% Water Ingestion Test
- 470 ml Water Slug Ingestion Test
- Successful Completion of all Tests
- Inlet Particle Separator Provides Protection

MQT Endurance Cycle



subsequently verified by comparing the number of hot section time-temperature index counts accumulated on an engine-mounted history recorder from the MOT testing with the experience from 12,000 hours of flight testing.

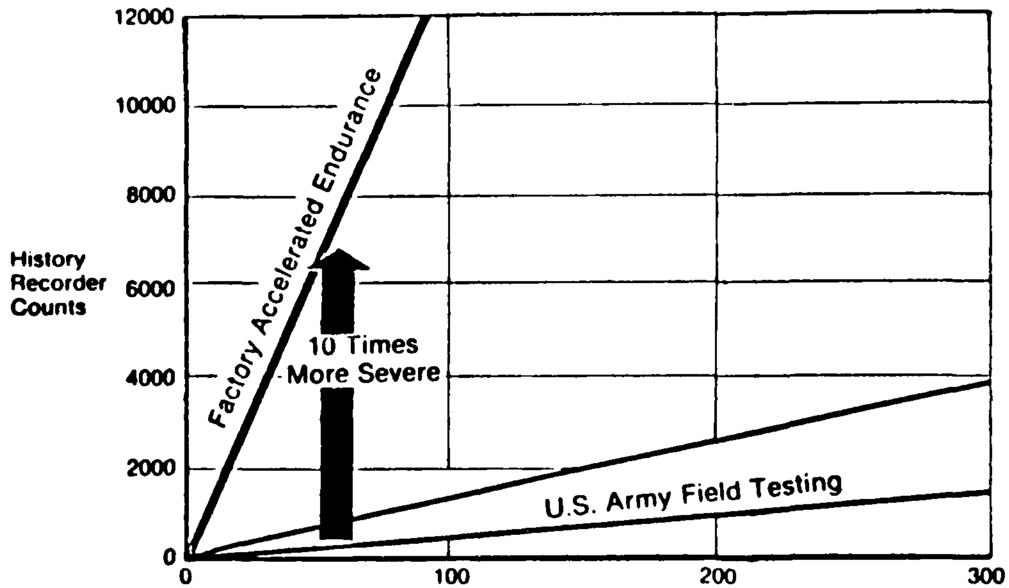
Additional accelerated engine life verification was obtained early in the development program through an extensive engine control and accessory component test program which included more than 137,000 test hours.

During the entire 8200 test hour development program, Development Problem Reports were issued by T700 Evaluation Engineering to the T700 Reliability operation who screened, coded and converted each chargeable failure or problem into a Malfunction Summary Report. This data was used by the Reliability operation in their analyses and predictions. A compilation of these Malfunction Summary Reports was issued to the UTTAS P.M.O. bi-monthly as a contractual line item CDRL #A060 of Contract #DAAJ01-72-C0381.

Each and every Malfunction Summary Report discrepancy was addressed and corrective action taken.

In addition to the close attention given to Reliability during the engine development program, Maintainability engineers worked closely with T700 Evaluation Engineering monitoring assembly/disassembly problems encountered by development assembly personnel. Many maintainability improvements were also effected during the development program by this close attention to Maintainability.

Lessons Learned



Factory Testing Much More Severe Than Field Experience

DESIGN LIMIT QUALIFICATION TESTING SUMMARY

- FIRST T700 DEVELOPMENT ENGINE TO TEST FEB. 1973.
- DEVELOPMENT/QUALIFICATION PROGRAM COVERED 4 YRS/8200 TEST HOURS.
- TWO NEW ARMY HELICOPTER FLIGHT TEST PROGRAMS IN PARALLEL WITH T700 ENGINE DEVELOPMENT PROGRAM.
- R&M DATA TAKEN THROUGHOUT DEVEOLOPMENT PROGRAM AND USED IN R&M ANALYSES.
- MAJOR EMPHASIS PLACED BY BOTH ARMY AND GE ON ACCELERATED ENVIRONMENTAL TESTING AND EXTRA SEVERITY ENDURANCE TESTING.
- PROGRAM OBJECTIVE TO REACH EARLY ENGINE MATURITY BEFORE INTRODUCTION INTO PRODUCTION.

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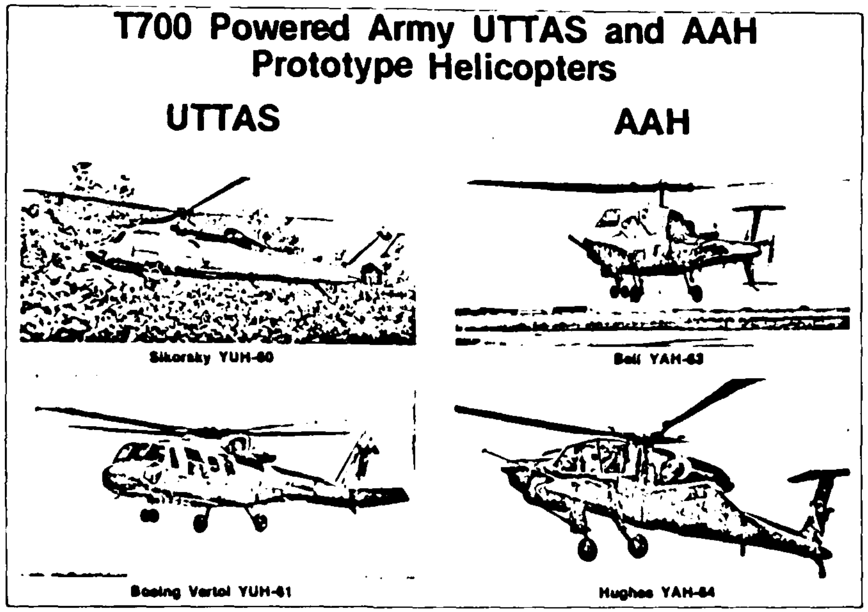
AVM INTEGRATION TESTING

The T700-GE-700 Development/Qualification Program was unique in that simultaneous with the development of the engine, four (4) different helicopter manufacturers were designing, building, and flight testing new helicopters for the U.S. Army's UTTAS and AAH Programs with all four (4) helicopters powered by the new T700-GE-700 turboshaft engine.

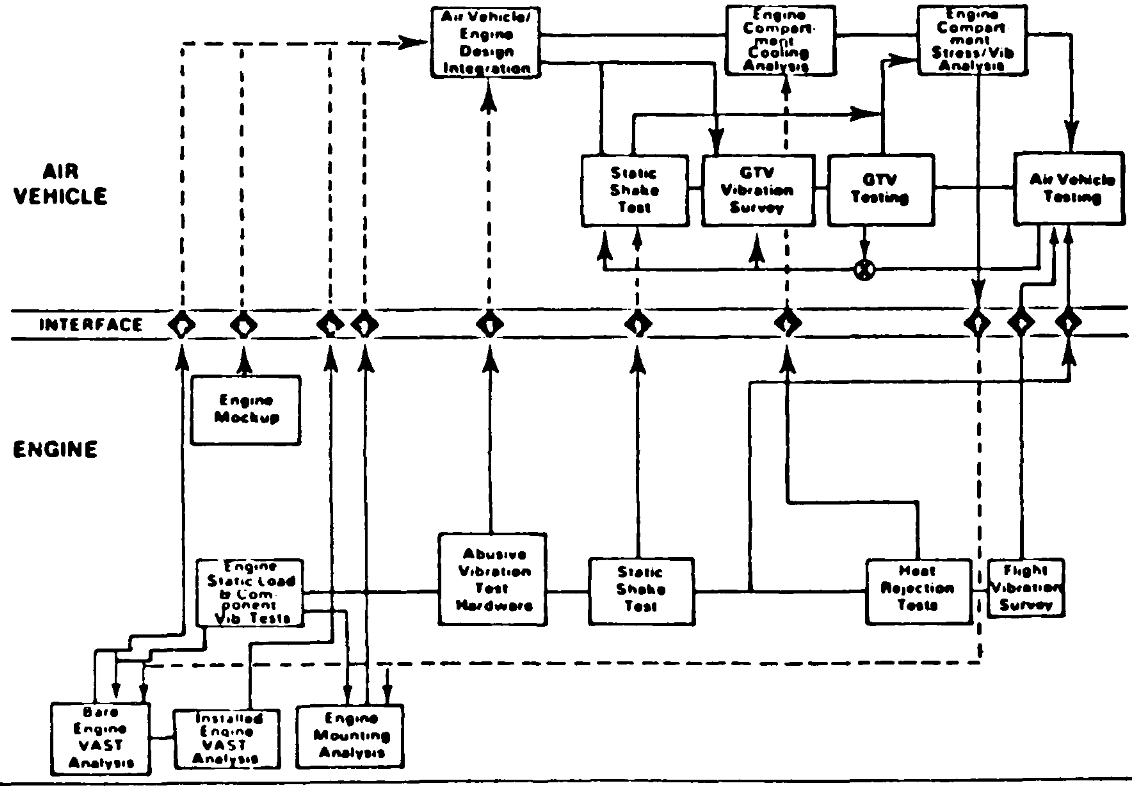
A key factor in integrating a single engine configuration into four helicopters was a thorough, pre-field test propulsion system integration effort: factory engine environmental and "fleet leader" testing, repeated Army/GE/AVM design and test reviews, and factory performance and vibrational testing for each installation.

T700 Identical Engine



Competitive Systems

UTTAS/AAH
Typical Integration Plan



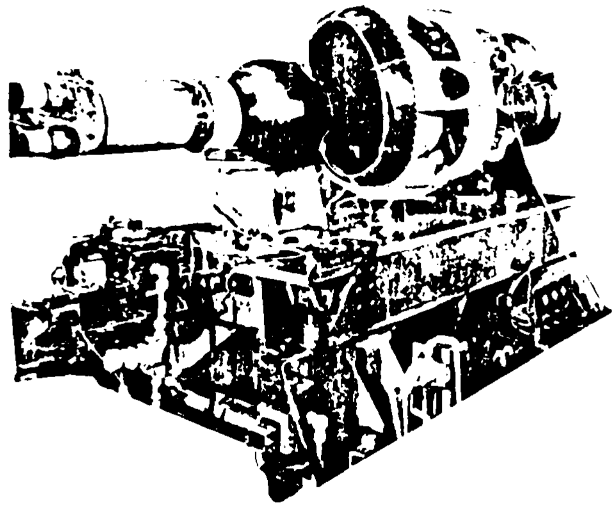
Inlet/Exhaust

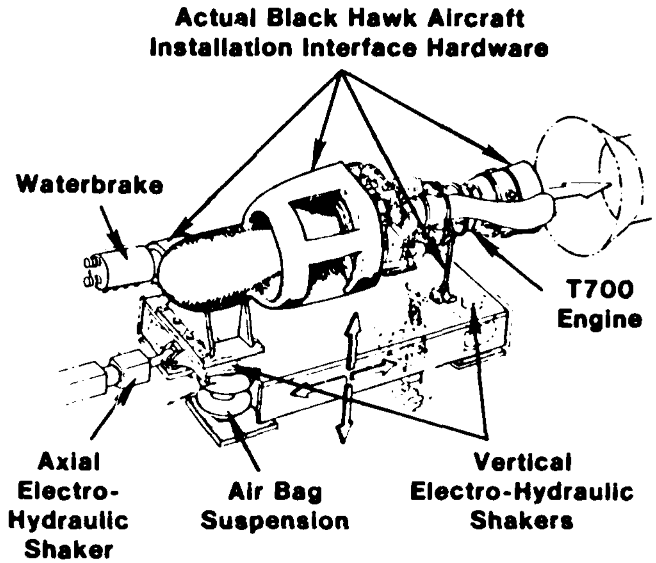
Inlet aerodynamic performance for various installation configurations was analyzed with the Inlet Particle Separator component test stand. This facility allows multi-location pressure traverse readings at the entrance to the axial compressor, thus allowing performance losses due to the airframe inlet/engine separator combination to be evaluated. Exhaust system performance was obtained by installing AVM hardware on development engines and evaluating operational horsepower differences between the engine exhaust referee duct (for spec rating performance) and the AVM exhaust ducts.

Abusive Vibration Testing

More than 300 engine test hours were conducted to evaluate operation of the T700 when mated with actual UTTAS and AAH installation hardware. This test used 3 hydraulic shakers to simulate low frequency aircraft vibratory inputs (4-50 Hz) and also accounted for max amplitude high frequency inputs by deliberately unbalancing the engine gas generator and power turbine rotor assemblies. Testing included more than 50 endurance hours at maximum steady-state vibration limits (low frequency), and several hours at maximum transient limits.

ABUSIVE VIBRATION TEST RIG





Simulates Engine/Aircraft Installation Operating Conditions

T700-92(11-78)

Cooling

Primary emphasis for evaluating UTTAS nacelle cooling systems was ensuring the presence of sufficient cooling flow to meet engine component temperature limits. AAH aircraft have integral Infrared Radiation Suppressor Systems which require cooling airflow up to 8 lbs/sec per engine to meet exhaust gas temperature requirements. The main cooling component testing objective was to verify that significant engine rotating component rubs would not be caused by localized engine casing shrinkage resulting from uneven cooling flow distribution.

As a result of the above factory integration testing, several minor interface problems were uncovered which were addressed very early in the AVM's bed phase.

Test Support

The UTTAS and AAH testing ultimately was conducted at over eleven different sites, and GE provided 24 hour on-site technical coverage for all operating sites throughout the 24-month program.

Additional significant field test support included GE-Lynn installed temperature, stress, vibration, and aero instrumentation on 24 XT and YT700 engines. Key engine operating parameters were monitored and recorded by GE's Edwards team during all four GTV pre-flight qualification tests (PFAT) and all four in-flight engine vibration surveys. Each vibration survey included measurements from 18 engine mounted accelerometers and 26 strain gages per aircraft. GE was responsible for signal processing, recording, and analyzing all parameters.

Throughout the test programs, the Army-owned SRD engines located in Lynn provided a means to quickly factory-investigate field revealed problems. These engines were also used for qualifying design fixes.

AVM INTEGRATION TESTING SUMMARY

- GE PROVIDED 24 HOUR ON-SITE TECHNICAL COVERAGE FOR ALL FOUR (4) AVM's DURING RED/GCT PHASES OF THE UTTAS AND AAH PROGRAMS.
- KEY ENGINE OPERATING PARAMETERS WERE RECORDED DURING AVM FLIGHT TEST PROGRAMS PROVIDING NEEDED INFORMATION ON INSTALLATION CHARACTERISTICS, I.E., VIBRATION, BAY COOLING, ETC.
- FACTORY DEVELOPMENT ENGINES SPECIFICALLY DESIGNATED FOR SRD INVESTIGATION TESTING IN SUPPORT OF THE AVM's PROGRAMS PROVIDED EXPEDITIOUS RESOLUTION/CORRECTIVE ACTION FOR OPERATIONAL IDENTIFIED PROBLEMS.

RELIABILITY GROWTH TESTING

Maturity Program

Overall UTTAS Program timing planned by the Army provided for Competitive Test (GCT) of the two different aircraft, each of which was powered by the same configuration T700. The test was begun at about the same time that engine MOT was completed. Under prior program standards, engine qualification would be considered complete at this time and the engine would have been committed to production. At this point, a post-MOT program was initiated with the goal of accumulating additional endurance experience and subjecting the engine to more LCF testing.

The overriding purpose of this Maturity Program was to provide a mature, reliable engine prior to full rate production. To accomplish this, the following objectives were established:

- Develop high initial Mean Time Between Failure-Require Overhaul (MTBFRO).
- Establish sound field maintenance procedures and intervals.
- Identify unique installation-related failure modes.
- Establish program for smooth transition to production manufacture.

The approach selected was to conduct accelerated, severe, abusive tests so that the required production target dates were assured.

A secondary benefit of the Maturity Program was that it provided a highly valuable period to resolve residual problems uncovered in the field and factory programs and any that might evolve from the aircraft GCT. In addition, a smooth transition to Production through Producibility and Manufacturing Technology programs was made possible, as well as the implementation of cost reduction programs prior to production.

Maturity Program Scope

Objective

The overriding objective of the Maturity Program was to provide a mature engine prior to full-scale production. To accomplish this the following specific goals were established.

- Develop high initial Mean Time Between Failure Requiring Overhaul (MTBFRO).
- Establish sound field maintenance procedures and intervals.
- Identify unique, installation-related failure modes.
- Establish programs for smooth transition from development to production manufacture.

To meet deadline targets, the approach selected was to conduct abusive and severe accelerated testing.

Program

For maximum effectiveness, the program was divided into two major efforts:

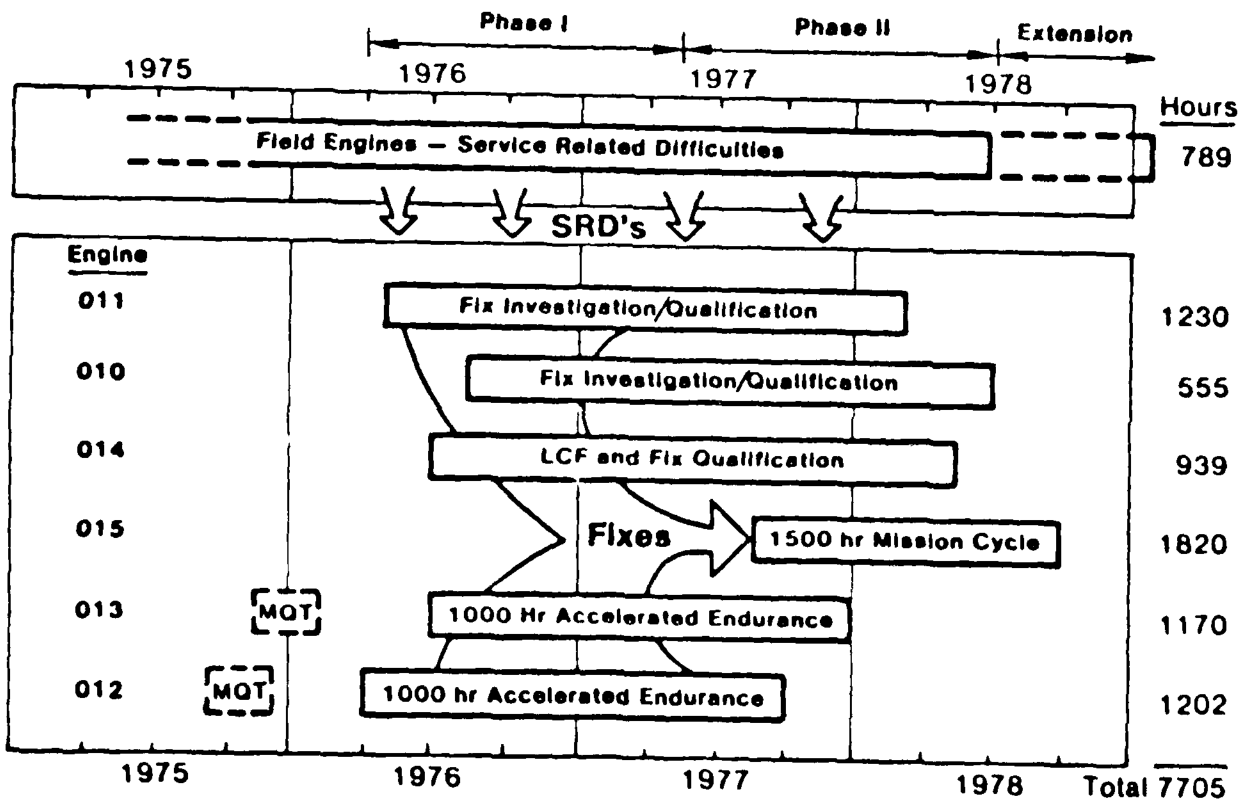
- Field
  - Support accelerated air vehicle testing
  - Update engines to latest configuration
  - Repair/overhaul as necessary
  - High time analytical inspections
- Factory
  - Two 1000-hour accelerated endurance tests
  - 1500-hour mission cycle test
  - LCF test (3500 cycles)
  - SRD/Fix qualification program
  - Qualification of production parts list

The Maturity Program was divided into two major parts for maximum effectivness.

- Factory
  - Two 1,000-hour accelerated endurance tests.
  - 1,500-hour mission test cycle.
  - Low Cycle Fatigue test (3,500 cycles).
  - Service Revealed Difficulty/Fix Qualification Program.
  - Qualification of Production Parts List.

- Field
  - Support accelerated aircraft test program.
  - Update prototype engines to latest configuration.
  - Repair/overhaul as necessary.
  - Perform high time analytical inspections.

Factory Program

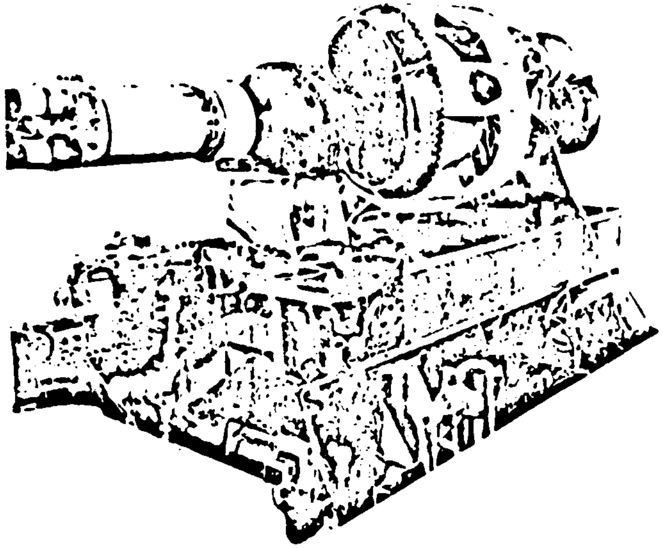


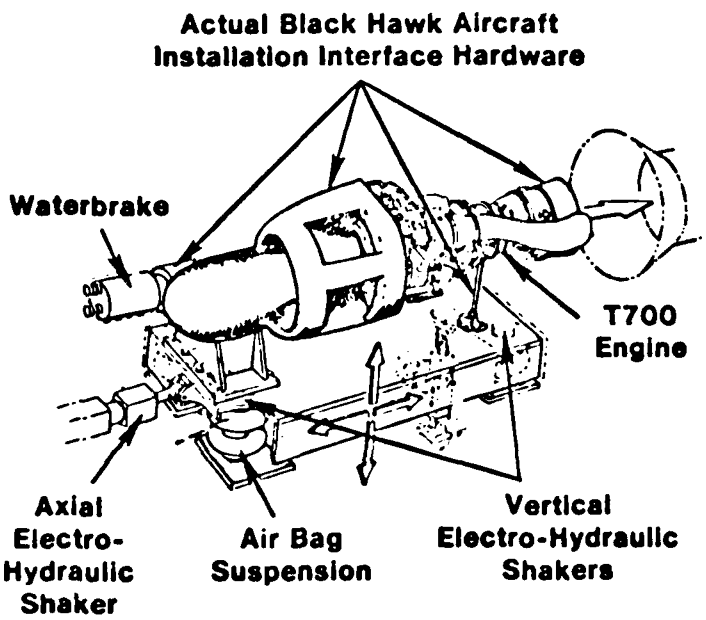
Immediately following the completion of the Qualification Program and the maintainability demonstration, the two MOT engines were reassembled and began running to accumulate the 1,000 hours on each. Any "failures" during this period of intensive endurance testing were considered as successes since they identified weaknesses in the system that could be resolved, endurance tested, and qualified for initial production. Approximately one year after initiation of these 1,000-hour endurance tests an Accelerated Simulated Mission Endurance Test (ASMET - Ref. pg IIE-36) was initiated.

At this point it might be best to highlight the 1,500-hour ASMET mission cycle test vehicle. As indicated in the illustration, the engine was supported by the actual aircraft mount system and also had the airframe inlet system, exhaust system, and control/sensing and fuel connections applied to simulate the aircraft installation. The entire test vehicle was installed on a vibration test stand and simultaneously subjected to the full range of frequencies characteristic of the helicopter installation and an engine operating cycle of increased severity containing significantly more transient operation than the previously conducted endurance tests.

Concurrent with these factory tests, flight test engines were generating service problems (SRDs). Subsequent design improvements were made against these SRDs and were incorporated into the ASMET engine to make it as close as possible to the production configuration.

1500 Hour Mission Cycle Test

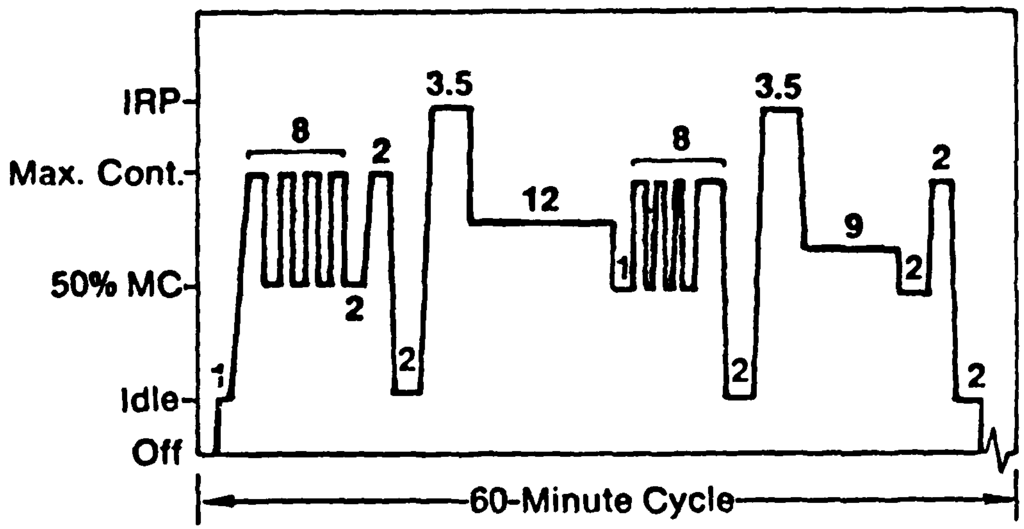




Simulates Engine/Aircraft Installation Operating Conditions

1,500-Hour Mission Cycle Test

Power Spectrum



- 18,000 Major Thermal Cycles
- Severity Ratio vs. Field Operation
  - 3:1 Stress Rupture
  - 1.5:1 LCF

1500 Hour Mission Cycle Testing

- Army Maturity
- Simulates Aircraft Mission/Environment
- Equivalent to $\gtrsim$ 5000 Mission Hours
  - Hot Section Life
  - Low Cycle Fatigue
- On-Condition Maintenance
- Full Mission Life Demonstrated Before Production

All field operations support during the Maturity Program was provided by the Integrated Logistics Support Management Team. This effort included deployment, at a number of operating sites, of necessary spare parts, special ground support equipment, and technically qualified field representatives. Engines used during this phase of the field program were Flight Rated engines updated to MOT configuration plus some maturity design improvements. The update of these engines and subsequent initial repair engines were processed at the General Electric Depot Service Facility.

Coordination of field maintenance tasks for installed engines was conducted with the airframer. Technical Manuals and Repair Parts and Special Tools Listing were reissued reflecting updates to the mature engine configuration immediately after MOT. All field maintenance, troubleshooting and repair was conducted against these documents to "test" them for accuracy and adequacy in the hands of the user. Depot manuals reflected the same updates, again as a base for improvements determined from experience.

Maturity Program Results

A number of field problems were exposed during the severe competitive evaluation of the air vehicles. The most important of these corrected were redesign of the Number 3 Bearing and the Power Takeoff Assembly. Other improvements included the Hydromechanical Unit (fuel control) and a new high pressure fuel pump, lower sensitivity chip detector, new power turbine shaft seals, and an improved airseal to reduce Electrical Control Unit operating temperatures. All of these changes were developed and qualified for first production engine introduction, thereby eliminating all known in-flight shutdown and mission abort causes experienced in GCT.

First hand observation of field operations also had indicated areas where maintenance procedures and some design features could be modified--or in some cases be eliminated--to decrease field maintenance actions by as much as 85%. It is interesting to note at this point that the top three problems on the Army's list were the frequency of adding oil, oil sampling and oil filter changes. All items the engineer had little concern about previously!

The accelerated factory tests did identify new failure modes as indicated by the chart. Most of these were fixed for first engine production. Without the maturity experience these problems would have remained hidden for one to three years or more based on average military use. The result would have been expensive programs of a fail-analyze-fix nature followed by retrofit.

Maturity program testing also led to a number of design changes for performance improvements. Following changes to the compressor and combustor, throttle stall margin and deceleration stall margin were improved by more than 30%, greatly enhancing operational suitability. The power turbine was improved to increase its efficiency as well as for better maintainability and reduced cost.

Logistics support benefits derived from the results of the Maturity Program were many. Materiel support requirements for the fully operational system were established for spare parts and spare engines, and ground support equipment was designed and qualified. Support facilities were set up and qualified as required, such as the depot/overhaul shop and central warehousing. Field procedures and depot repair procedures were developed and verified. Documentation was updated to reflect actual field operation and issued before first fielding the production aircraft. In effect, an experienced organization and system were in place to support the UH-60A from the very beginning.

RELIABILITY GROWTH TESTING SUMMARY

- GOVERNMENT COMPETITIVE TESTS (GCT) OF THE TWO (2) HELICOPTER SYSTEMS, UTTAS AND AAH, BOTH STARTED ALMOST SIMULTANEOUSLY WITH COMPLETION OF THE T700 MQT PROGRAM.
- ALL FIELD SUPPORT DURING MATURITY PROGRAM WAS PROVIDED BY INTEGRATED LOGISTICS SUPPORT MANAGEMENT TEAM.
- FIELD PROBLEMS IDENTIFIED DURING THE GCT's WERE PROMPTLY RESOLVED AND FIXES INCORPORATED INTO THE PRODUCTION CONFIGURATION WHICH WERE QUALIFIED DURING THE FACTORY ENGINE MATURITY PROGRAM.

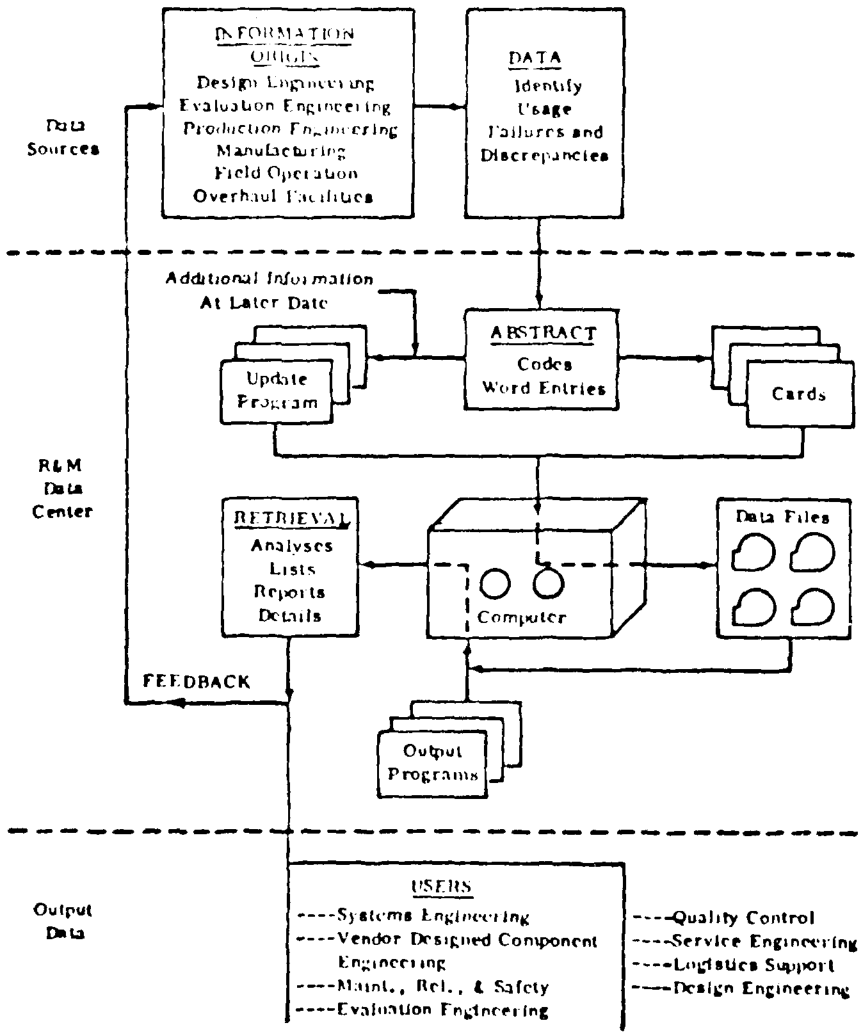
- GCT FIELD OPERATIONS POINTED UP SEVERAL AREAS WHERE MAINTENANCE PROCEDURES COULD BE IMPROVED OR ELIMINATED.
- ACCELERATED FACTORY TESTS IDENTIFIED SEVERAL ADDITIONAL PROBLEMS THAT WERE FIXED AND QUALIFIED FOR FIRST PRODUCTION.
- WITHOUT MATURITY PROGRAM THESE PROBLEMS WOULD HAVE BEEN HIDDEN FOR 1-3 YEARS IN THE FIELD.
- MATURITY PROGRAM ALSO PROVIDED THE LOGISTIC COMMUNITY THE OPPORTUNITY TO PUT AN EXPERIENCED ORGANIZATION/SYSTEM IN PLACE TO SUPPORT THE UH60A BLACK HAWK FROM THE VERY BEGINNING.

DEMONSTRATION TESTING

Attachments M5 and M6 of the [illegible] for the 1500 SHP Gas Turbine Engine for the UTTAS very clearly stated the requirements for both the Reliability and Maintainability Program plans to include demonstration tests indicating when and how these demonstrations would be accomplished.

From the very beginning of the T700 Development Qualification Test Program, every malfunction or discrepancy was documented both in the factory as well as at the various UTTAS and AAH Flight Test Programs. Factory development problems were documented on Development Problems Reports (DPR's) and field problems were documented on DD-[illegible] forms. As shown in the Data Flow Diagram, the Reliability Operation processed/analyzed the various reports, thus every T700 engine test hour, both in the factory and in the field represented an input for the T700 engine reliability program. This reliability tracking analyses were continued as part of the post MQT Maturity and Life Verification Testing. Approximately 35,[illegible] engine operating hours were logged by the time the first T700-GE-700 production engine was delivered in March, 1978, thus providing an excellent reliability demonstration base upon which to base the engine's Mean Time Between Failures (MTBF).

With the introduction of T700-powered Black Hawks into the field in 1979, a field tracking system was initiated which is described in the R&M Field Problem Reporting Tracking System section of this report.



Data Flow Diagram

Reliability Demonstrations

The following statements have been extracted from the T700 Reliability program plan:

9.0 TEST AND DEMONSTRATION

9.1 RELIABILITY DEMONSTRATION TESTS - The following table lists the primary tests which shall be used for reliability demonstration of the engine and its components:

Test	Engine Operating Hours
MOT (Endurance Run)	300 (two 150-hour tests)

9.3 OTHER TESTING APPLICABLE TO RELIABILITY MEASUREMENT - Testing and demonstration shall be conducted in accordance with the approved test plans submitted IAW Data Items DI-T-1900 and addendum dated 15 Dec. 70, Coordinated Test Plan, and DI-T-1903 and addendum dated 19 Mar. 71, Part, Component or Subsystem Test Plan(s). All of the following testing assist in verification of reliability. Much of this testing is at severity levels significantly different than operational service. Test time and failure shall be used in reliability quantitative assessments only after test/service severity can be established. However, some of these tests shall not be included in the failure/test time record applicable to reliability prediction/assessment because of their purely abusive character.

Testing

- P - All Endurance Testing Prior to PFR or MQ Endurance Test
- P - PFR Endurance Test
- P - MQ Endurance Test (JP4 & MIL-L 7808)
- P - Endurance Test (JP5R & MIL-L-23699)
- V - Sand Ingestion Tests
- P - Low Cycle Thermal Fatigue Test
- V - Engine Overspeed Test
- V - Engine Overtemperature Test
- V - Salt Corrosion Susceptibility Test
- V - Loss of Oil Test
- V - Engine Overtemperature Control System Test
- V - Engine Overspeed Control System Test
- V - Fire Resistance Test
- V - Engine Component Explosion-Proof Test
- V - Engine Component (Excluding Fuel Pump) Room Temperature Endurance Test
- V - Fuel System Icing Test
- V - Fuel Room Temperature Endurance Test
- V - Fuel Pump Cavitation Test
- V - Oil Tank Test
- V - Component (Except Fuel Pump Operational)
- V - Electrical Component Environmental Tests
- V - Accessory Drive Test
- V - Fuel Pump Qualification Tests

Symbols: P = Probable quantitative measurement input.
V = Probable qualitative input.

Part reliability improvement testing shall be conducted as required.

Maintainability

A very early maintainability demonstration was funded by the U.S. Army and was accomplished on the ATE (GE12) Demonstrator engine in 1971 and with the award of the Development Contract in March, 1972, the Maintainability Program Plan for the T700 engine was set into action. The following paragraphs are extracted from this plan which describe the three (3) official maintainability demonstrations required by contract:

11.0 MAINTAINABILITY CHECKS/DEMONSTRATIONS - The contractor shall conduct the following maintainability checks and demonstrations and shall coordinate this effort with all other interfacing specialty disciplines and the ILS program. The plans for conducting the first engine teardown and the maintenance evaluation will be submitted in the Monthly Progress Report, in accordance with Data Item DI-R-1741 and addendum dated 19 March, 1971, Part, Component or Subsystem Test Plan(s).

11.1 FIRST ENGINE TO TEST TEARDOWN - The first engine built shall be disassembled/assembled to evaluate the removal/reinstallation of LRU's and basic engine components during the 14th month of the contract. The maintenance actions shall be performed by Engineering Evaluation and Test personnel and results shall be documented and submitted in accordance with Data Item DI-R-1741 and addendum dated 19 March, 1971, Design Review and Demonstration Summary. The engine and consumable material used in the maintenance actions shall be provided by T700 EF&T. Development shop support equipment shall be used. Measurement (by stopwatch) of task times shall be made during this demonstration. Data shall be recorded by Maintainability personnel and will be entered in MFA data and used in the MFA. Comparison of these times with the time specified in paragraph 3.36 of the PIDS shall identify areas of deviation from the guaranteed removal time and areas for potential reduction of maintenance times.

11.2 MAINTENANCE EVALUATION - An engine of the PFRT configuration shall be disassembled/assembled to evaluate the removal/reinstallation of LRU's and basic engine components during the 28th month of the contract. The maintenance action shall be performed by T700 EF&T personnel. The engine and consumable material used in the maintenance actions shall be provided by T700 EF&T. Development - shop support equipment shall be used. Data shall be recorded by Maintainability personnel and shall be entered in MFA data and used in the MFA.

This evaluation shall demonstrate the progress toward achievement of the guaranteed removal/replacement times and shall be used to recommend design changes if required. The results shall be documented and submitted in accordance with Data Item DI-R-1741, Design Review and Demonstration Summary.

11.3 MAINTAINABILITY DEMONSTRATION - A detailed plan for formal demonstration of the guaranteed removal and replacement times specified in paragraph 3.36 of the PIDS shall be developed and submitted to the Army for approval prior to commencing the demonstration on an engine of the MQT configuration during the 34th month of the contract. The engine and consumable material used in the maintenance demonstration and test shall be provided by T700 EE&T.

11.3 The Maintainability Demonstration Plan shall identify the conditions, team, support material to be used in the demonstration in accordance with MIL-STD-471 and comply with the following procedures:

- Maintenance actions shall be timed.
- Maintenance actions shall be conducted with the engines centered in a 20.0 foot diameter circle which shall be clearly marked on the floor.
- Anyone inside the 20 foot diameter circle shall be considered as working on the engine and maintenance man hours calculated accordingly.
- A penalty of 0.5 man hours shall be assessed for the use of each special tool during a maintenance action.
- The engine shall be in a "ready for issue" condition prior to and subsequent to each maintenance action.
- No more than two men shall be allowed to work on the engine simultaneously.

11.3.2 The demonstration shall consist of the following maintenance actions to be performed in accordance with the maintainability demonstration plan.

- Periodic inspection shall be performed ten times.
- A complete disassembly and assembly of the engine shall be performed on time to demonstrate the times for all maintenance actions. The incremental task times shall be recorded and the tasks associated with each maintenance action shall be accumulated to verify the guaranteed times are achieved.
- Ten removal and reinstallation actions of components from each of four categories shall be performed. The components shall be selected at random by the Procuring Activity subsequent to the complete disassembly/assembly of the engine. Final task listing shall be submitted in the formal demonstration plan, in accordance with paragraph 11.0 Maintainability Checks/Demonstrations.

11.3.3 The demonstration shall be accomplished in the Contractor's training school using experienced personnel as mechanics, authorized ground support equipment, manuals and MEA tasks and task sequences. The engine shall be "ready for installation" condition prior to and subsequent to each maintenance action.

The results of the formal demonstrations shall be documented and submitted in accordance with Data Item DI-T-1906, Test and Demonstration Reports.

Each of the above official Maintainability Demonstrations were accomplished on schedule.

MAINTAINABILITY DEMONSTRATION

The official MOT Engine Maintainability Demonstration was completed in May, 1976, and was performed with U.S. Army mechanics from the T-School at Ft. Eustis, VA. This demonstration was observed by General J. Lauer, UTTAS PMO and William J. Crawford, III, T700 Project General Manager, as shown on the attached photo (Ref. pg. IIF-54).

Following this official demonstration at General Electric, the same Army Team then traveled back to Ft. Eustis where the Army mechanics performed identical tasks on the Lycoming built T53-L-13B. The actual maintenance times were compared in a final report issued by Mr. Charles R. Brooks and Mr. Michael P. West from the Directorate for Product Assurance of the U.S. Army Aviation Systems Command, dated October, 1976. A copy of the executive summary from this report is presented on page IIF-56. As may be noted from this report, there was a 72.3 percent reduction in line maintenance and 55.5 percent overall through all levels of maintenance when compared to this 1960 vintage engine.

R76AEG044
G.E. CLASS 2
30 JUNE 1976

R76AEG044

T700-GE-700 ENGINE

MQT - ENGINE MAINTAINABILITY DEMONSTRATION

by
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T700 Maintainability & Human Factors Eng.
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Sensitive to General Electric Company

CONTRACT NO. DAAJ01-72-C-0381

Each transmittal of this document outside the Department of Defense must have prior approval of the UTTAS Project Manager, USAMC, P.O. Box 209, St. Louis, Missouri 63166

AIRCRAFT ENGINE GROUP
GENERAL ELECTRIC COMPANY
LYNN, MASSACHUSETTS

GENERAL ELECTRIC

TECHNICAL INFORMATION SERIES

Title Page

AUTHOR	SUBJECT	NO.
DC Murray *DC Murray*	T700 MQT Engine Maintainability Demonstration	R76AEG044
TITLE T700 MQT Engine Maintainability Demonstration against PIDS Quantitative & Qualitative Requirements — G.E. CLASS II — GOVT. CLASS Unc		DATE 30 June 1976
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		GOVT. CLASS Unclassified
		NO. PAGES

SUMMARY

The Maintainability Demonstration was conducted on MQT engine SN 207-010-4A, in compliance with Prime Item Development Specification (PIDS) No. AMC-CP-2222-02000 A para. 4.4.18, in Bldg 1-70 and 3-40 General Electric Co., Lynn, MA.

The Maintainability Demo. Plan TM 76AEG1036 with PIDS Appendix 30 & 50 detailed the procedure, the schedule and requirements. Per PIDS Para. 3.36, GE planned and demonstrated compliance with removal and replacement times as well as exhibiting, identifying & calculating the Quantitative and Qualitative features/requirements. GE demonstrated conformance to the PIDS requirements. Army mechanics demonstrated confidence that they could achieve similar/same/better times. Both teams completed more tasks and in better times than scheduled. Its recommended that this report be accepted as evidence of successful completion of the Maintainability Demonstration against PIDS requirements.

KEY WORDS
T700 MQT Engine, Army, Maintainability, Demonstration

CONTRACT NUMBER DAAJ01-72-C-0381 SPONSORING ORGANIZATION US Army Mat'l Command

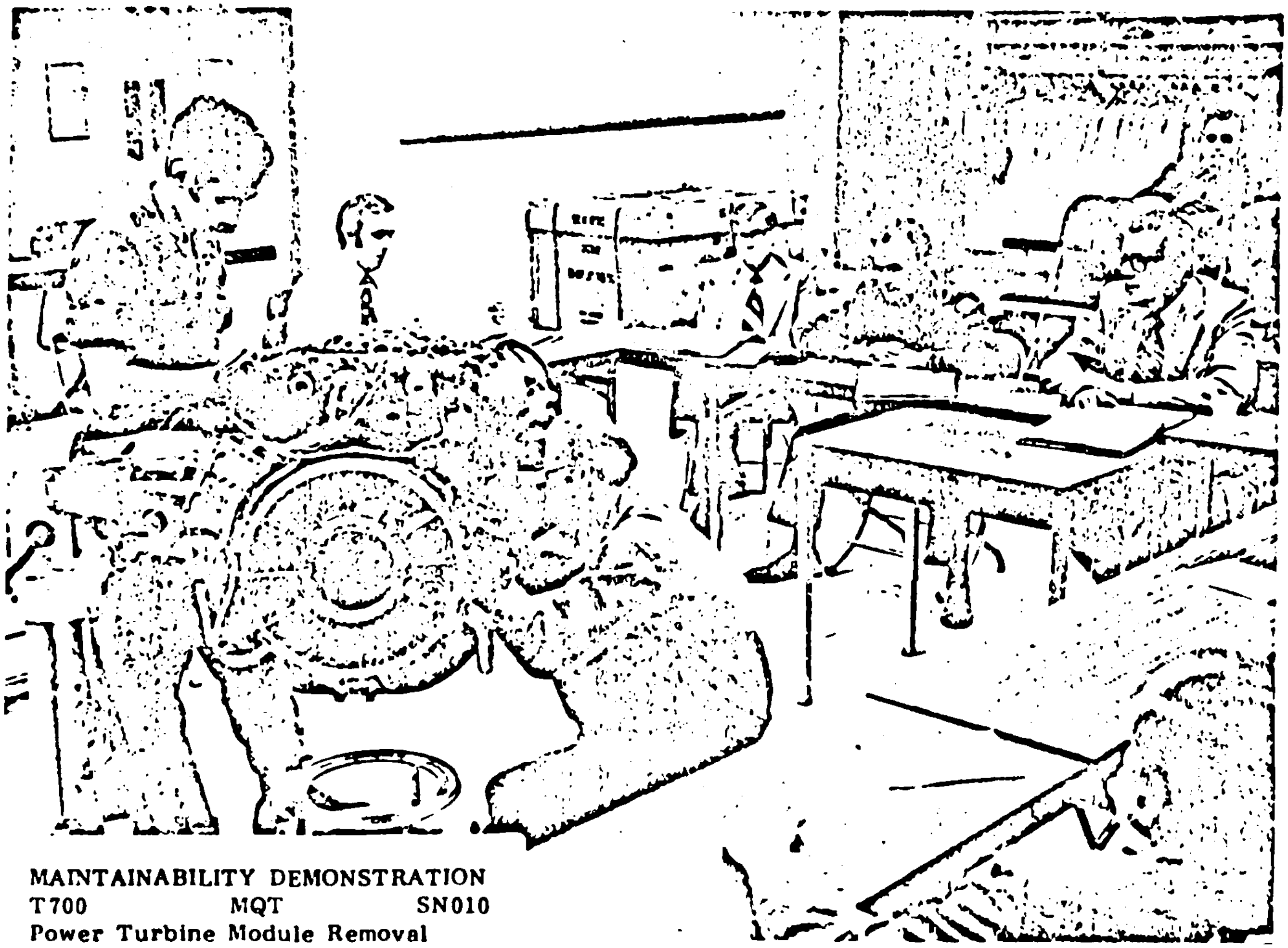
APPROVED BY *J.M. Wellborn* J.M. Wellborn (AUTHOR'S MANAGER)

DEPT./OPERATION LEO Engine Life Management (ORGANIZATION)

LOCATION Lynn, Massachusetts

AIRCRAFT ENGINE GROUP

BY 717



MAINTAINABILITY DEMONSTRATION
T700 MQT SN010
Power Turbine Module Removal
R76AEG044

Maintainability Demonstration

Remove and Replace

Modules (Elapsed Time)	PIDS Spec	U.S. Army Demo	GE Official**
Power Turbine	38 Min.	32	38
Hot Section	74	55	63
Cold Section	128	78	86
Accessory	36	24	23
WRA's (Man Minutes)			
Hydromechanical Control	22	8	13
Wiring Harness	25	12	16
Thermocouple Harness	13	15*	13
Electrical Unit	8	5	7
Primer Nozzles	10	3	5
Torque Sensors	9	5	5
Np Sensor	9	5	5
Igniters	9	4	8
Separator Blower	8	2	3
Anti Icing/Bleed Valve	8	4	7
Radial Drive Shaft	8	2	3
Exciter	7	6	6
Lube Scavenge Pump	7	4	4
Alternator Stator	7	3	4
Oil Filter Bypass Sensor	5	3	4
Oil Cooler	5	4	3
Oil Filter	4	1	2
Ignition Leads (Two)*	4	6*	8*
Engine History Recorder	6	3	3
Fuel Boost Pump	4	3	3
Fuel Filter Assembly	8	3	4

*Exceeds Spec
**Incorporated in E1220 Spec

T700-21(060981)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

MAINTAINABILITY COMPARISON EVALUATION BETWEEN THE T53-L-13B AND T700-GE-700 GAS TURBINE ENGINES

BY

CHARLES R. BROOKS

MICHAEL P. WEST

OCTOBER 1976

US ARMY AVIATION SYSTEMS COMMAND

DIRECTORATE FOR PRODUCT ASSURANCE

R&M DIVISION

ST. LOUIS, MO.

EXECUTIVE SUMMARY

1. Background: It has been recognized that one of the key elements of reducing operating and support costs is improving the maintainability of fielded equipment. This idea was reinforced by the Commander, DARCOM, when he requested that AVSCOM take an existing or developmental system and improve its maintainability. The program that we developed to pursue this objective was to compare the maintainability aspects of the T700 with an existing similar system, the T53 engine. There was a comprehensive maintainability program during the T700 development whose primary objective was to reduce maintenance task times in the field. This report provided the documentation of the success of the T700 maintainability program and recommended areas of improvement for both the T700 and T53 engines.

2. Objectives: To show that the maintainability program during the T700 development has achieved the objective of reducing field maintenance task times when compared to the maintenance times required for functionally similar tasks on the T53.

3. Research Methods: The approach to the comparison of the two engines was:

- Compare task times between the T53-L-13B and T700-GE-700 for organizational, intermediate and depot level maintenance.
- Compare special tool requirements for each maintenance level.
- Identify potential maintainability improvement candidates for the T53-L-13B.
- Identify established maintenance techniques at depot level which may be better than the proposed new maintenance techniques for T700.

4. Findings: There was a reduction of 72.3 percent in the task times at aviation unit and intermediate maintenance for the T700 engine. Overall, there is about 55.5 percent improvement in man-minutes on the T700 through all levels of maintenance. The T53 manual identifies 225 special tools. Even more significant is that the T700 required no special tools for field maintenance, whereas the T53 required 25 special tools. The T53 manual lists 85 special tools for field maintenance.

Several areas of maintainability improvements were identified for both the T53 and the T700. On the T53 the elimination of safety wire would be a major change in design for maintainability. The T700 currently has a method of power turbine wheel blade retention which can be improved.

From our study it is apparent that the maintainability program accomplished its objective of reducing field maintenance by the use of modular and line replaceable unit design concepts.

DEMONSTRATION TESTING SUMMARY

- R&M DEMONSTRATIONS REQUIRED IN RFQ.
- DEVELOPMENT AND AVM FLIGHT TEST PROGRAMS PROVIDED EXCELLENT RELIABILITY DEMONSTRATION DATA BASE.
- FOLLOW-ON MATURITY/LIFE VERIFICATION PROGRAM PROVIDED VALUABLE RELIABILITY GROWTH DATA FOR EARLY PROBLEM RESOLUTION PRIOR TO FIRST PRODUCTION SHIPMENTS.
- THREE OFFICIAL MAINTAINABILITY DEMONSTRATIONS PERFORMED DURING THE T700 DEVELOPMENT/QUALIFICATION PROGRAM (PERFORMED ON FIRST ENGINE TO TEST 'FETT' PFRT CONFIGURATION AND GE 12 DEMONSTRATOR).
- OFFICIAL MQT ENGINE MAINTAINABILITY DEMO PERFORMED BY ARMY "GREEN-SUITERS" AND OBSERVED BY UTTAS PMO AND T700 PROJECT GENERAL MANAGER.
- FOLLOW-ON MAINTENANCE COMPARISON DEMO PERFORMED ON 1980 VINTAGE ENGINE BY U.S. ARMY AT FT. EUSTIS--SHOWED 55% OVERALL REDUCTION IN MAINTENANCE MAN HOURS AT ALL LEVELS.

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OPERATIONAL TEST & EVALUATION

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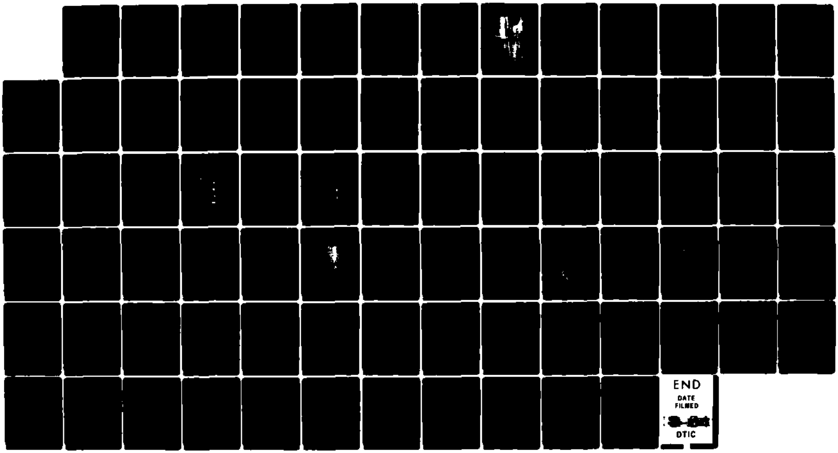
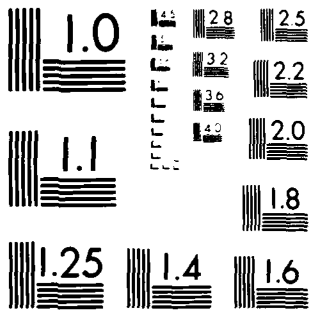




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

T700 engine development and testing benefited due to simultaneously developing the engine and four different experimental helicopters. The four aircraft were involved in two major flyoff competitions, UTTAS and AAH. All four types of twin-engined experimental helicopters used identical versions of the YT700-GE-700 turboshaft engine.

The T700 and UTTAS were simultaneously developed under auspices of the Materiel Development and Readiness Command's (DARCOM) UTTAS Program Manager's office, with AAH starting almost 12 months later.

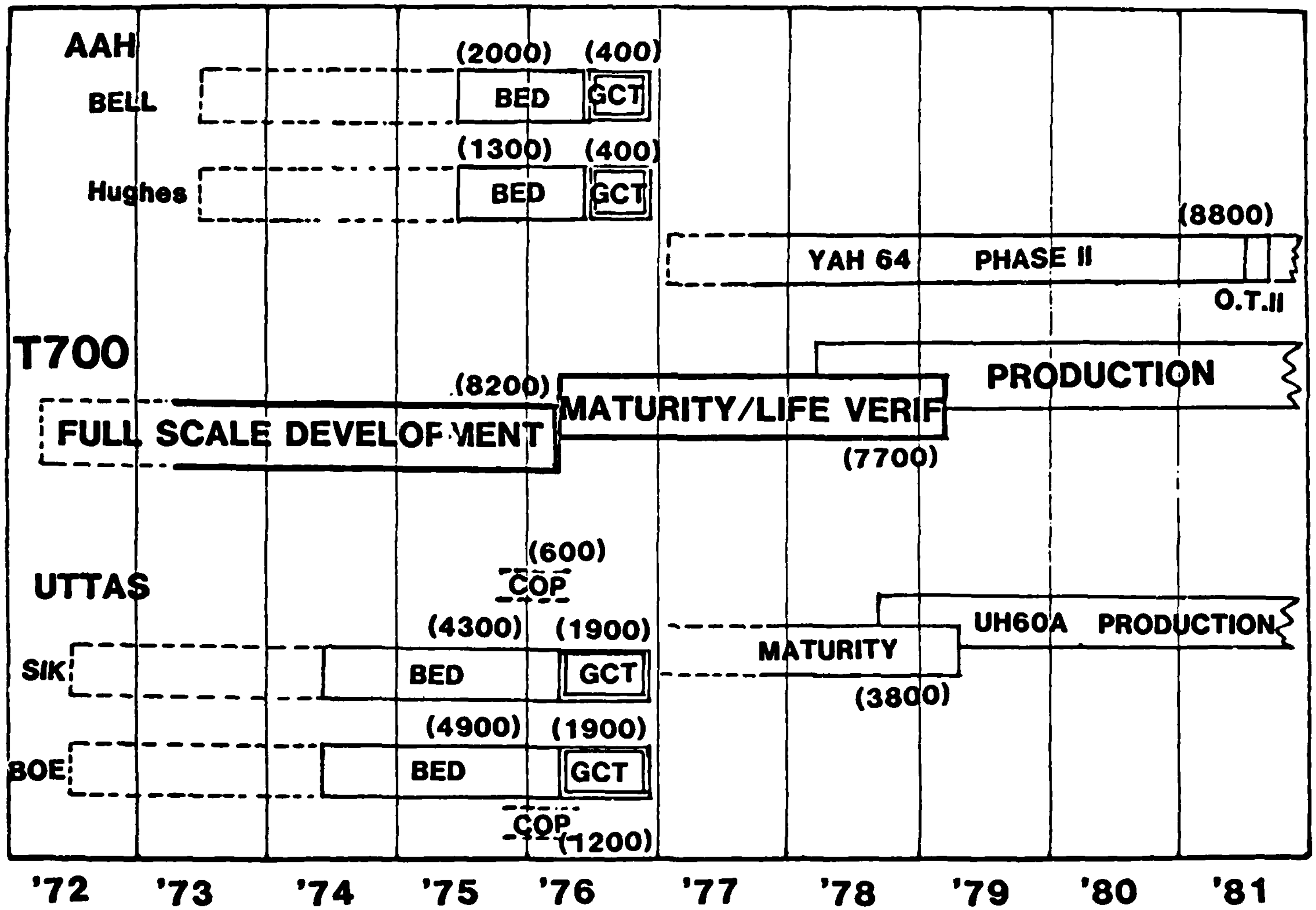
Engine reliability data and installation "lessons learned" from the 18,000 engine test hours accumulated during the UTTAS and AAH Programs represent an invaluable opportunity to examine four different propulsion systems in a concentrated time period and apply the "Lessons Learned" from actual operational testing into early corrective actions.

As an integral part of the UTTAS Program the T700 design had to reflect key aircraft concerns for system survivability, reliability and maintainability. For example, AVUM level (flight line) maintenance task times were significantly reduced compared to 1960 vintage Army helicopter engines.

Development Concept - The Army's UTTAS testing philosophy included testing that took the prototype aircraft to Ft. Campbell and meeting predetermined goals using the standard Army field team. Both Boeing Vertol and Sikorsky were required to demonstrate all production aircraft systems in the working Army environment prior to production contract award.

The Army was also looking for a full exploration of the UTTAS flight envelope, demonstration of C-141 and C-5A air transportability, and the ability to perform defined UTTAS missions in all types of adverse environmental conditions: icing, heat, cold, night flying, and forward operating sites.

T700/BLACK HAWK/APACHE DEVELOPMENT PROGRAM



PHASE 2 PROGRAM

The Phase 2 program was a 56-month full-scale engineering development wherein the two Hughes helicopters from Phase 1 were modified to the latest configuration. Three more helicopters were built, and development of the HELLFIRE missile, 30 mm cannon, and 27.5 rocket subsystems completed. Also competitively developed were the target acquisition-designation sight and pilot's night vision sensor. The subsystem and all mission equipment were integrated and tested. The Army Operational Test II was completed with the APACHE accumulating over 400 flight hours during June-August 1981. A total of over 4,000 test hours were flown on the YAH-64 prototypes. The residual AAH weapons system testing and other related essential activities were also completed.

PRODUCTION

Long Lead Time contracts for production of the APACHE were awarded in February 1981. The initial production contract was awarded 15 April, 1982.

During the entire AAH Flight Test Program, GE technical representatives documented all engine discrepancies and this data was processed through the Lynn Product Data Center and T700 Reliability Operation for inclusion in the Reliability Analyses/Predictions.

In order to develop UTTAS derivatives for the commercial transport market, Sikorsky and Boeing Vertol each built a Company-Owned Aircraft (COA). Operating simultaneously with the Army program, these two aircraft acquired an additional 1200 engine hours of YT700 experience.

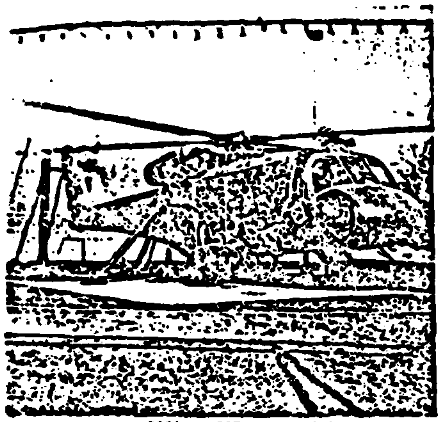
The primary purpose of the BED Phase flight test activities was to explore aircraft performance and handling qualities, establish aircraft vibrational characteristics, and to perform a series of propulsion system surveys. Surveys included:

- Engine vibration and stress
- Inlet distortion
- Control Compatibility
- Bay Cooling
- Suction fuel system performance

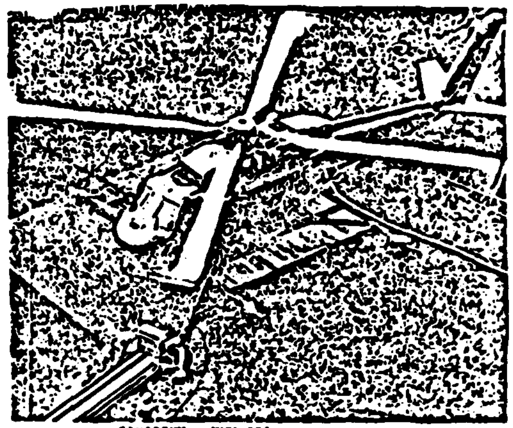
All BED Phase testing was completed at Sikorsky's Stratford, Connecticut test center and the Boeing Vertol/Grumman joint test facility on Long Island.

All engine problems were documented by GE technical representatives on DV7 forms and processed through the Lynn Product Data Center and the T700 Reliability operation.

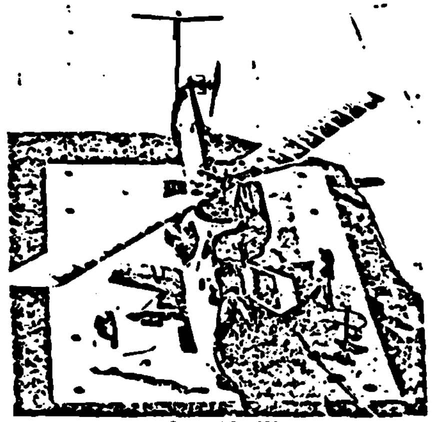
T700-GE-700 POWERED GROUND TEST VEHICLES



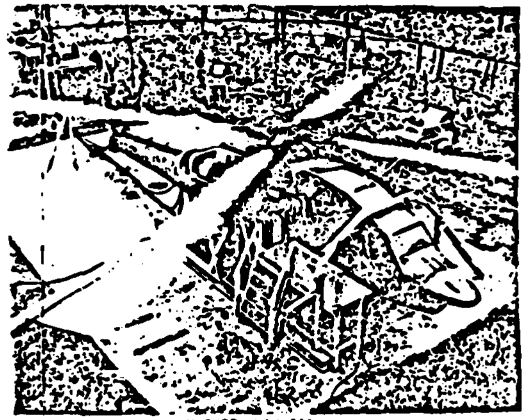
BOEING VERTOL YUH-61A



SIKORSKY YUH-60A



BELL YAH-63A



HUGHES YAH-64A

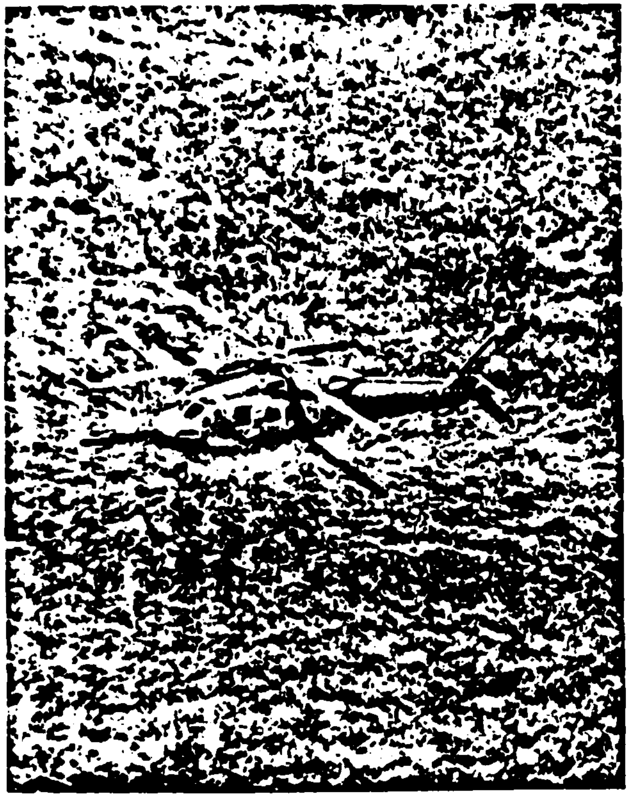
5250 ENGINE OPERATING HOURS

Government Competitive Test (GCT) - Government competitive testing started in March, 1976 at Ft. Rucker, AL., using two aircraft from each AVM. In May, 1976, aircraft performance and handling quality testing began at Edwards Air Force Base with the third Army-owned aircraft per AVM. During the next seven months, these six aircraft achieved a total of 3800 engine test hours at six different operating test sites: Army User Evaluations were conducted at Ft. Rucker., AL., Ft. Campbell, KY, and at a high altitude Bishop, CA site. Aircraft icing evaluation was conducted at Ft. Wainwright, Alaska. Each AM's GTV was also used for cold/hot environmental ground testing at Eglin Air Force Base, FL.

The primary purpose of GCT testing was to put the production "prototype" UTTAS under a rigid Army User evaluation with the main emphasis on operational realism. Not only were User flight tests flown by randomly selected Army pilots, but all AVUM level (flight line) maintenance was performed by representative Army mechanics, all of whom were monitored by an "Army" of reliability and maintainability data collectors. Almost 50 percent of total UTTAS experience occurred with Army pilots and mechanics operating in the User's world.

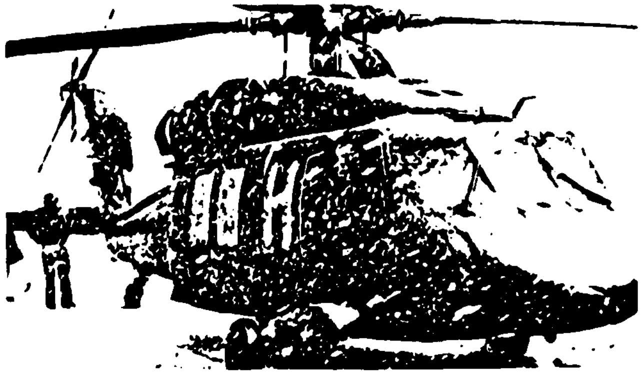
During the entire BED Phase and GCT, GE technical representatives documented every engine problem/discrepancy and this data was factored into the Reliability Analyses/Predictions and also provided a 'real world' operational experience base.

Tested in the Real World



Army Test at Ft. Campbell

Army Test at Ft. Rucker



"Arctic" Test at Ft. Drum

T700-727(071878)

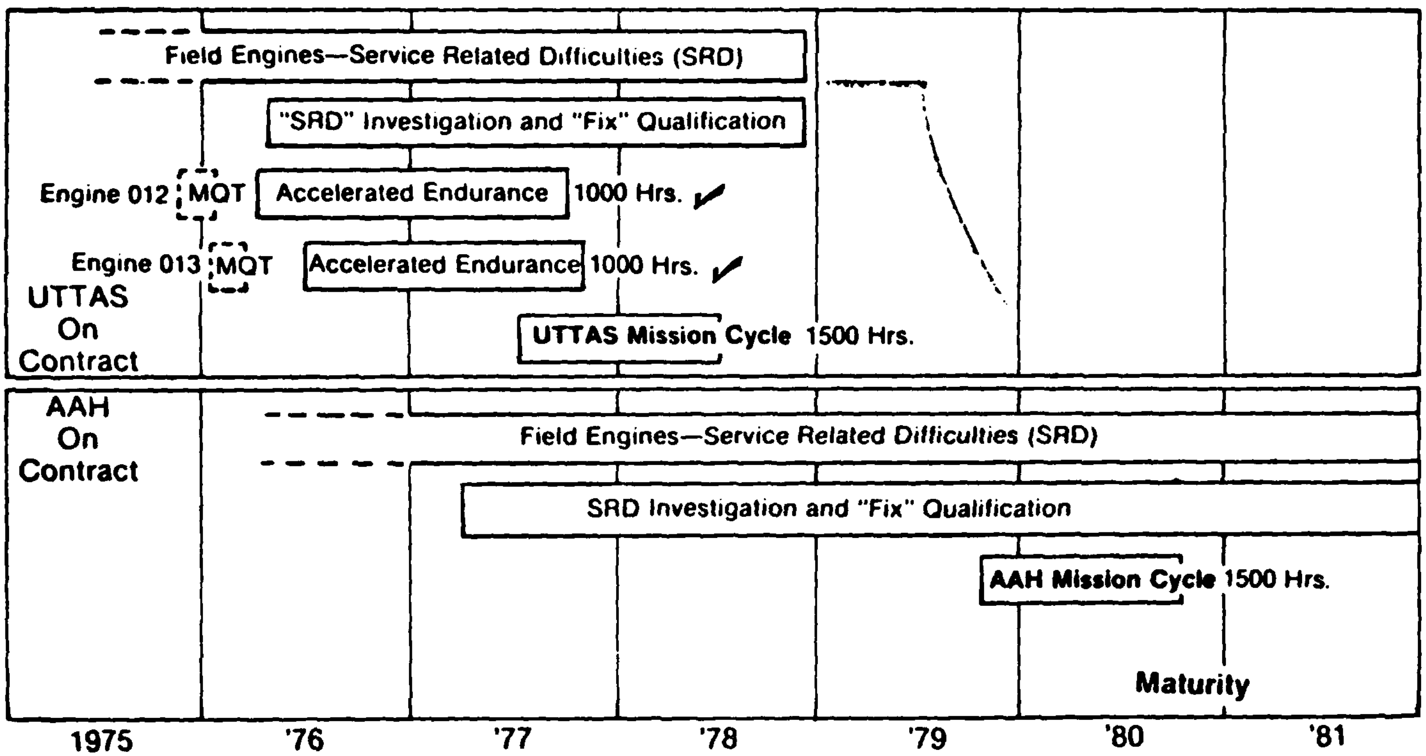
GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

<ins>UTTAS Maturity Program</ins> - Following the completion of the Government Competitive Tests (GCT's), the Sikorsky-built YUH-60 was selected for production and designated as the Black Hawk.

A follow-on Maturity Flight Test Program contract was awarded to both Sikorsky and General Electric. The three prototype YUH-60's and the GTV were subjected to a limited update program and the YT700 engines were returned to the factory and updated to incorporate several fixes which had been identified during both the Development/Qualification Program and the BED Phase and GCT field programs. These engines were designated with an 'R' after the serial number to indicate the retrofit.

The Black Hawk Maturity Flight Test program resumed in late 1976 and continued into 1979 with an overlap of the Black Hawk Production Program. During this Maturity Flight Test Program several official aircraft qualification tests were completed as well as envelop expansion. GTV running continued to qualify main transmission and drive train components. During this maturity Program approximately 3800 engine hours were accumulated and throughout this program GE technical representatives continued to document all engine discrepancies to further expand the Reliability base on the engine.

Engine Factory Maturity Programs



AAH PROGRAM

As an outgrowth of an RFP issued in late 1972, Hughes Helicopters and Bell Textron were selected by the Army in mid-1973 to compete in the AAH flyoff competition. Both AVM's had selected the standard T700-GE-700 turboshaft engine (already being developed for UTTAS) as an integral part of their propulsion system. The Army's Phase I Program conformed to the classic flyoff competition format: Basic flying qualities were to be demonstrated along with an assessment of the technical risk areas, but subsystem development with subsequent integration and aircraft maturity were minimized in order to expedite selection of the winning AAH design and introduction of the production Attack Helicopter. Unlike the UTTAS full-scale "fly ever[illegible]ng before you buy" approach, the AAH competitors did not need to demonstrate all the fire [illegible]trol, night flying, and weapons systems that were to be eventually incorporated into the Phase 2 development and production models. The Army conducted abbreviated User aircraft evaluation. Flight evaluation was conducted by experienced Army pilots, with Reliability and Maintainability monitoring by Army data collectors.

The AAH Program was originally scheduled to be 16 months shorter than the UTTAS competitive cycle - 35 months from initial contract award to completion of the GCT Program. Cost increases and aerospace material shortages in the late 1973, early 1974, time period contributed to a six-month program slippage; however, the AAH Phase I Program and GCT were completed 12 months faster than the UTTAS Program. Still, the AAH flight test program averaged 20 percent more YT700 engine operating hours/aircraft/month than the UTTAS Army program (63 versus 53 hours).

AAH Phase I - Phase I Testing (equivalent to the UTTAS RED Phase) started with GTV operation in June, 1975. By the end of ground testing in May, 1976, the two competitors had completed 1300 hours of XT and YT700 engine operation. Unlike UTTAS which utilized GTV testing to demonstrate long-term "fleet leader" reliability, AAH GTV testing was limited to 50 hours of pre-flight aircraft qualification and subsequent follow-on qualification (up to 150 hours) of the propulsion system and drive train.

AAH flight testing was initiated in September, 1975 and, by the conclusion of Phase I in May, 1976, both Hughes and Bell had accumulated 1700 YT700 engine operating hours with the two flyable aircraft operated by each company. Since UTTAS testing had already been in progress for 12 months, many initial engine operating problems and troubleshooting procedures had already been resolved, thus significantly speeding engine/airframe integration during the initial portion of AAH flight test. The AAH flight test program was supported by 28 YT engines evenly distributed between the two test sites and four SRD engines kept at GE's Lynn, MA facility for rapid verification and qualification of field related problems.

The primary goal of Phase I flight testing was a preliminary exploration of the aircraft performance envelope and validation of basic handling qualities. In addition, some limited propulsion system flight surveys were conducted by joint GE/AVM teams and the basic 2.75 inch rocket and 30 mm gun systems were demonstrated. All ground and flight testing was conducted at each AVM's flight test facility: Hughes Helicopters at Palomar, CA and Bell Helicopter at Arlington, TX.

OPERATIONAL TEST AND EVALUATION SUMMARY

- T700 DEVELOPED SIMULTANEOUSLY WITH FOUR NEW EXPERIMENTAL HELICOPTERS -- A FIRST.
- PRE-FIELD TEST PROPULSION SYSTEM INTEGRATION EFFORT EMPHASIZED.
- OVER 18,000 ENGINE TEST HOURS ACCUMULATED VERY EARLY IN FOUR DIFFERENT HELICOPTERS MUCH OF WHICH WAS IN 'REAL WORLD' ENVIRONMENTAL CONDITIONS.
- R&M DATA FEEDBACK BY GE REPS FOR EARLY PROBLEM RECOGNITION/CORRECTIVE ACTION.
- R&M DATA FROM FIELD USED TO AUGMENT FACTORY DEVELOPMENT EXPERIENCE AND ACCELERATE R&M GROWTH.

FIELD DATA RETRIEVAL

The U.S. Army in the RFO for the 1500 SHP Gas Turbine Engine for the UTTAS, specified that the engine should have a "device on the engine to record overtemps, overspeeds, etc." As a result, an engine history recorder was included in the PIDS which was approved by the UTTAS PMO. The engine history recorder (EHR) measures operating time (hours), time-temperature index counts (counts as function of time above a temperature reference). Full Low Cycle Fatigue Cycles (LCF_1) and partial Low Cycle Fatigue Cycles (LCF_2).

During the first (3) years in service, the engine was covered by a Reliability Improvement Warranty Program. During this period, a special AVRADCOM form #DRSTS-O-256 Component Record for Intensive Management (CRIM) was employed at all Army installations operating UH-60A Black Hawks/T700 engines. This form was defined specifically for the T700 engine and included a block for the EHR readings. A list of some eighteen (18) high cost items were placed under CRIM tracking and a CRIM had to be filled out by the user any time one of these designated components was removed and returned to the Contractor. Unfortunately, no other official U.S. Army documented requirement exists to require the user to record the readings from the EFH.

Negotiations are currently underway with the Army for an Engine Health Monitoring Program which will require periodic readings of the EFH as well as EHR readings whenever an LRU or other engine component is removed. All R&M data to date has been provided by Contractor field representatives or phone calls to operational personnel at sites like Ft. Rucker, which no longer have field technical representatives.

CONTRACTOR'S INCENTIVE

The Government will pay the Contractor a Reliability Incentive for each hour that an engine or any of the Intensive Managed Items listed below which have accumulated 500 hours of running time without failure after receipt by the Government, and continues to operate without failure after 500 hours up to 750 hours during the period 1 May 1978 through 1 May 1981. This incentive will be calculated on a pro-rata basis as described in Contract DAAK50-78-C-0001.

Intensive Managed Items

History Recorder

Anti-Ice Valve

Electrical Control Unit

Ignition Exciter

Output Shaft Assembly

Power Takeoff Drive Assembly

Gas Generator Turbine Rotor

Stage 1 Nozzle

Combustion Liner

Gas Generator Turbine Stator

Power Turbine Module

Accessory Module

Fuel Boost Pump

Lube Pump

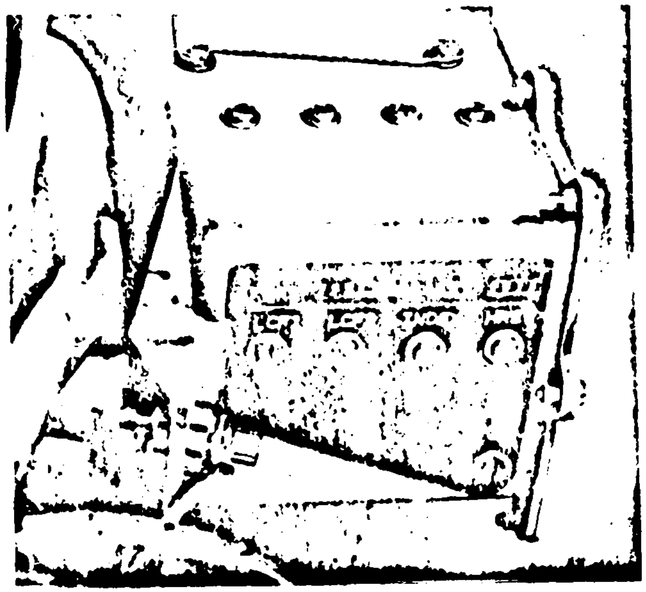
Sequence Valve

Partical Separator Blower

Hydro Mechanical Unit

T700 Engine and/or Cold Section Module

History Recorder Measures Life Expended



COMPONENT RECORD FOR INTENSIVE MANAGEMENT (CRIM)

Requirement Control Symbol DRC-

CONTROL NUMBER	FILE NUMBER	
100030	100030	W

SECTION A - COMPONENT/PART/MODULE IDENTIFICATION

1. PART NUMBER	2. SERIAL NUMBER	3. WORK UNIT CODE
4042T42G04	GJA00245	049706
4. NSN/MCN 2840 01H600387	5. FSCM 99207	6. NOMENCLATURE Exciter

SECTION B - DA FORM 2408-16 END ITEM IDENTIFICATION

7. PART NUMBER	8. SERIAL NUMBER	9. T700 ENGINE POSITION
		1 LEFT
		2 RIGHT
		3 NOT APPLICABLE

10. T-700 ENGINE HISTORY RECORDER READINGS: LCF 1 / LCF 2 / TTS / OP HOURS

11. SERIAL NUMBER OF HISTORY RECORDER

SECTION C - AIRCRAFT IDENTIFICATION

12. MODEL	13. SERIAL NUMBER	14. AIRFRAME HOURS

15. EFFECT ON MISSION		16. FAILURE DETECTED DURING	
A	EMERGENCY LANDING	A	SCHEDULED MAINTENANCE
B	ABORT	B	TEST
C	REDUCED PERFORMANCE	C	RUN-UP
D	NO EFFECT	D	FLIGHT
		E	OTHER - N/A

SECTION D - ACTION IDENTIFICATION

17. TYPE OF ACTION			18. MAN-HOURS FOR ACTION	19. CONDITION
	A	REMOVAL		X S SERVICEABLE
	B	INSTALLATION		U UNSERVICEABLE
	C	REPAIR	20. FAILURE CODE —	21. CUMULATIVE COMPONENT FLIGHT HOURS 0000
	D	OVERHAUL		
	E	TRANSFER		
X	F	GAIN		
	G	NOT REPAIRABLE	22. TIME SINCE LAST DEPOT REPAIR 0000	23. NUMBER DEPOT REPAIRS 0
	H	TESTED OK, NO REPAIR		
	J	NEW DESIGNATION		

24. UIC (This Action)	25. LEVEL	26. UIC (Shipped To)
K99207	—	KC11ACG

NARRATIVE

JULIAN DATE	SIGNATURE
8119	Q.C. Inspector

DARCOM Form 256 (TEST) 1 Feb 78 — Copy 1

FIELD DATA RETRIEVAL SUMMARY

- ENGINE HISTORY RECORDER REQUIRED BY RFQ.
- PROVISIONS MADE TO USE EHR DURING WARRANTY PROGRAM (FIRST 3 YEARS).
- NO OFFICIAL ARMY REQUIREMENT TO USE EHR.
- NEGOTIATIONS IN PROCESS FOR ENGINE HEALTH MONITORING SYSTEM.
- ALL R&M DATA TO DATE SUPPLIED BY CONTRACTOR TECH. REPS.

R&M FIELD DATA REPORTING/TRACKING

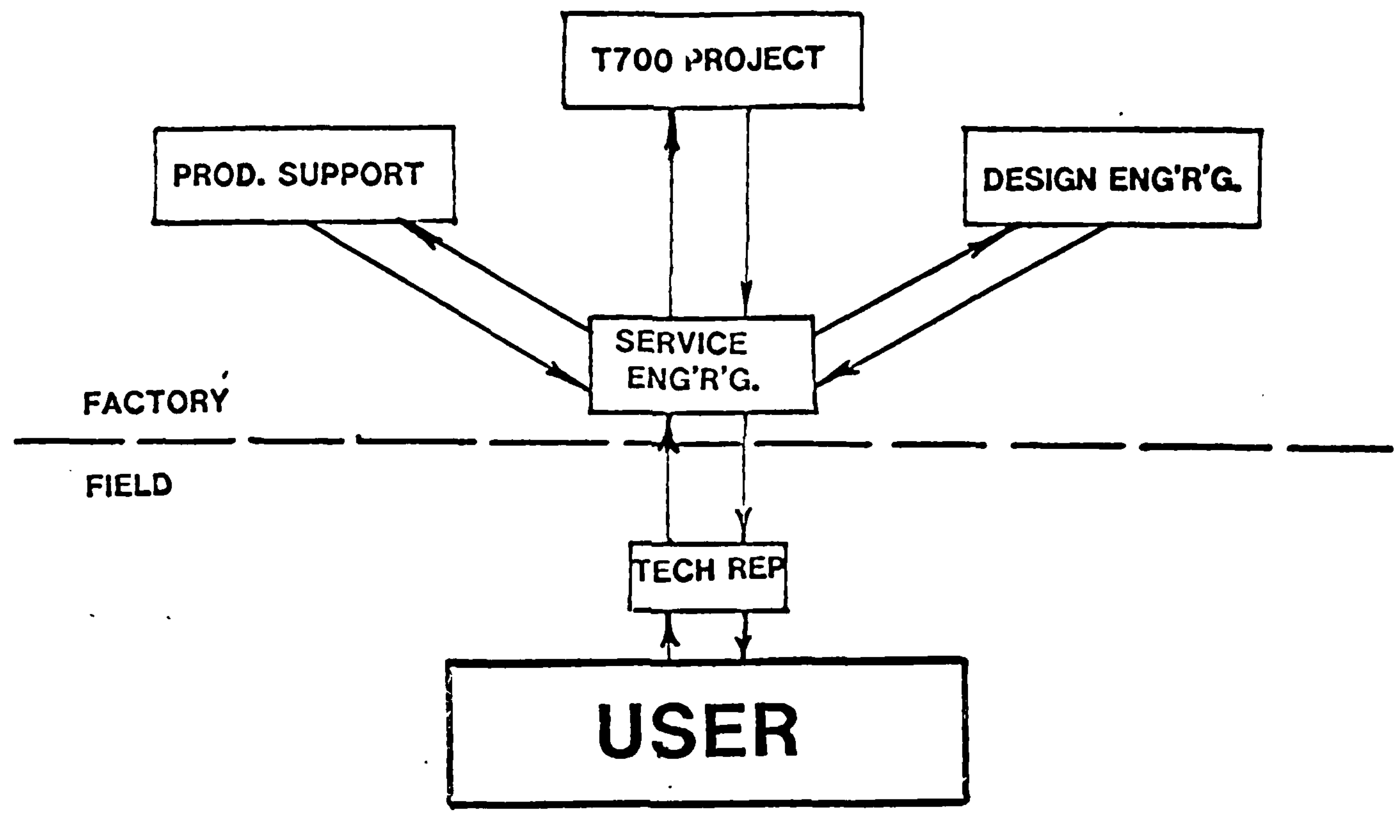
Since the first UTTAS YUH-60 flew at Sikorsky Aircraft in 1974, General Electric field technical representatives have been in place to provide technical assistance and to document all engine problems/discrepancies and report these back to the factory via DV-7 reports. These reports are inputted into the Problem Report file at Lynn Product Data Center (LPDC). In addition, the DV-7's also go to the T700 Service Engineering Operation. The assigned T700 Service Engineer screens the DV-7's and where required generates a Service Revealed Discrepancy (SRD) work request to the T700 Systems Engineering Operation requesting an engineering investigation/follow-up. These SRD investigations are reviewed with the PMO representatives at the Program Progress Review (PPR's) and later at the Component Improvement Program (CIP) reviews.

In addition, the T700 Reliability Operation also reviewed the DV-7's and where required converted the discrepancy to a Malfunction Summary Report (MSR). These MSR's were included in the offical bi-monthly Reliability Reports which were a contractual requirement through the full-scale Development/Qualification Program. These MSR's could only be closed out after concurrence by the local NAVPRO engineering representative.

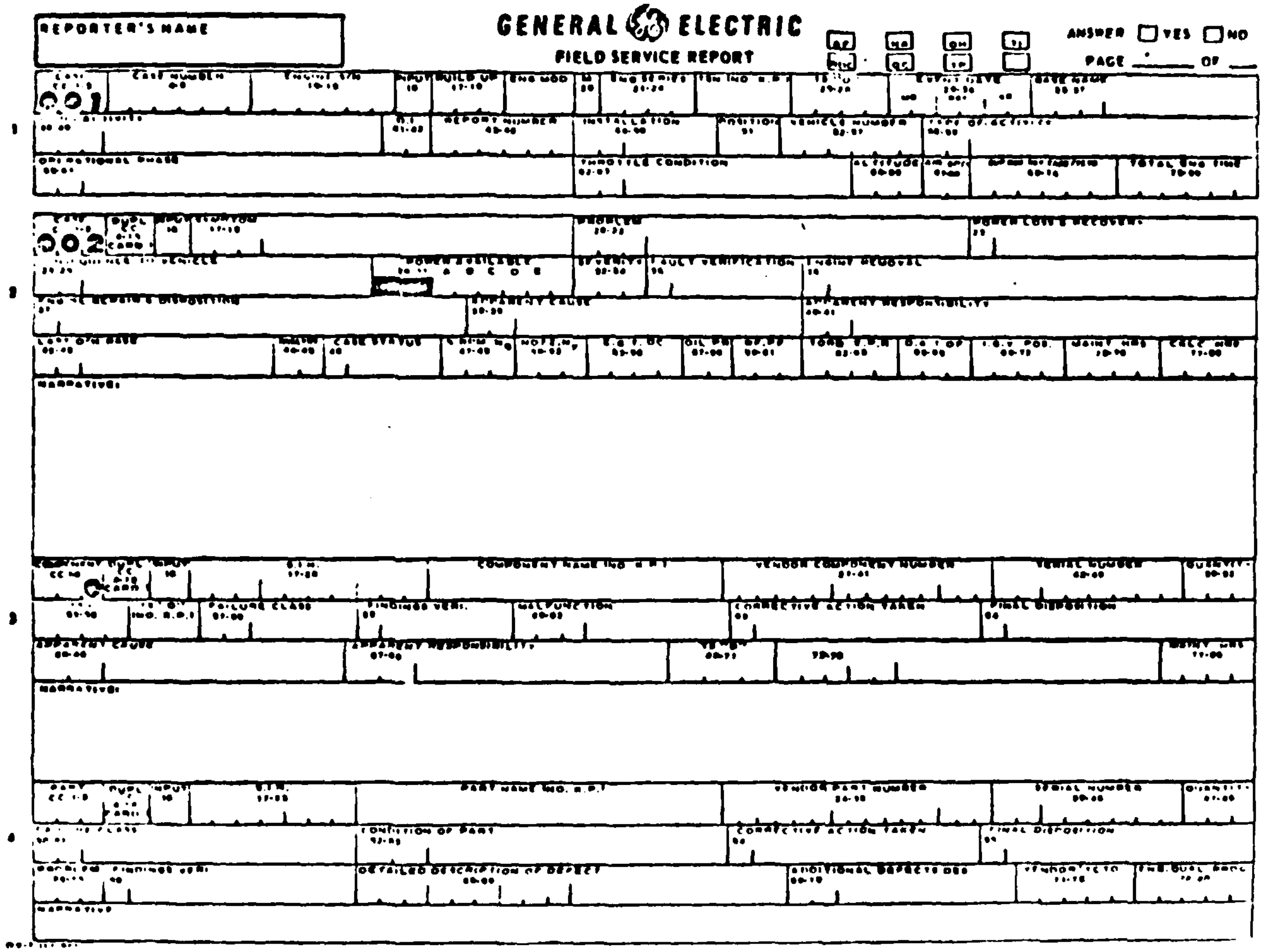
With the completion of the Development/Qualification program, all field generated SRD's are recorded in the Technical Letter Progress Report which is the official minutes of the former PPR's and now the CIP reviews.

Once a fix has been identified and approved by the PMO at the PPR or CIP review, the proposed change is submitted on an Engineering Change Proposal (ECP).

FIELD TECHNICAL SUPPORT



SERVICE ENG'R'G. ASSURES RAPID PROBLEM RESOLUTION


REPORTER'S NAME
GENERAL ELECTRIC
FIELD SERVICE REPORT
ANSWER YES NO
PAGE OF
CASE NUMBER
ENGINE S/N
BUILD UP
ENG MOD
ENG SERIES
REPORT NUMBER
INSTALLATION
POSITION
VEHICLE NUMBER
TYPE OF ACTIVITY
OPERATIONAL PHASE
THROTTLE CONDITION
ALTITUDE
TOTAL ENG TIME
002
PROBLEM
POWER LOSS & RECOVERY
POWER AVAILABLE
A B C D E
SEVERITY
FAULT VERIFICATION
ENGINE REMOVAL
APPARENT CAUSE
APPARENT RESPONSIBILITY
CASE STATUS
NARRATIVE:
S/N
COMPONENT NAME NO. & P/I
VENDOR COMPONENT NUMBER
SERIAL NUMBER
QUANTITY
FAILURE CLASS
FINDINGS VERI.
MALFUNCTION
CORRECTIVE ACTION TAKEN
FINAL DISPOSITION
APPARENT CAUSE
APPARENT RESPONSIBILITY
NARRATIVE:
PART NAME NO. & P/I
VENDOR PART NUMBER
SERIAL NUMBER
QUANTITY
CONDITION OF PART
CORRECTIVE ACTION TAKEN
FINAL DISPOSITION
DETAILED DESCRIPTION OF DEFECT
ADDITIONAL DEFECTS DES
NARRATIVE

1. ORIGINAL

SENSITIVE TO GENERAL ELECTRIC

20 MAY 1976

UTACC

RELIABILITY REPORTS:

- BI-MONTHLY PROGRESS REPORT
- ANALYSES, PREDICTION REPORT
- MALFUNCTION SUMMARY REPORT

Contract No. DAAJ01-72-C-0381

Data Item A008

AIRCRAFT ENGINE GROUP

LYNN, MASSACHUSETTS/CINCINNATI, OHIO

GENERAL ELECTRIC

SENSITIVE TO GENERAL ELECTRIC

MALF. SUM. RPT. NO: BV009 DATE: 3/12/76 AUTHOR: Berding/Scanlan

CORRECT. ACTION: STARTED: 12/20/75 INCORP: X T & [illegible]

REVIEW: [illegible] Design E.L.M. [illegible] U.S. Army [illegible] Evaluation

CASE CLOSED

Hydromechanical Unit P/N 6033T59P01 - Ng. hang up in the 30% to 50% speed range during start. Where discovered - during test of the BV YUH-61A OTV on engine 207107 installed in the No. 2 position. Maintenance action taken - line maintenance removed and replaced the HMU. S/N 80710. Previous Malfunctions - See MSR 105 & 193. Failure cause - See RFIAR Rpt 38. FMECA failure mode - change position. Corrective action - See RFIAR, Item 38, Table 1 Reliability Progress Report, 9.20.75.

For engines in service, the General Electric Company instituted a special R&M tracking system which is referred to as the "Bottom Line Measures" (BLM) system. This system utilizes the DV-7 data submitted by the field technical representatives and calculates ten (10) R&M parameters which address: 1) operating cost, 2) readiness, and 3) mission completion.

These ten (10) BLM's measure how well an engine is doing in service in the hands of the user. The BLM's measure <u>all causes</u> whether it be engine caused or non-engine caused.

Internally, a BLM report is issued Monthly and is calculated on a 90-day rolling average. The BLM's are also calculated on a yearly basis. These BLM reports are also reviewed at the PPR's and CIP reviews and copies of these reports are included in the Technical Letter Progress Report.

These BLM's are reviewed by top level GE management and emphasis placed where required to bring about improvements to the engine.

10 "Bottom Line" Measures

All Causes, Events

Measure	Category
• Shop Visit Rate per 1,000 EFH	Operating Cost
• LRU Rate, per 1,000 EFH, Including Engine Removals for Access	Operating Cost
• MMH, per EFH (Including Depot)	Operating Cost
• Ground Test Time, per EFH — Engine Maintenance	Operating Cost
• Parts Consumption Cost, per EFH / % Engine Price per 1,000 EFH	Operating Cost
• Parts Consumption and Labor Costs, per EFH at $30/Man-Hour	Operating Cost
• Engine Holes/Percent	Readiness
• MTBMA, Hours	Readiness
• Mission Abort Rate, per 1,000 EFH Hours	Mission Completion
• In-Flight Shutdown Rate, per 1,000 EFH for Twin Engine Aircraft	Mission Completion

M-119(103180)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

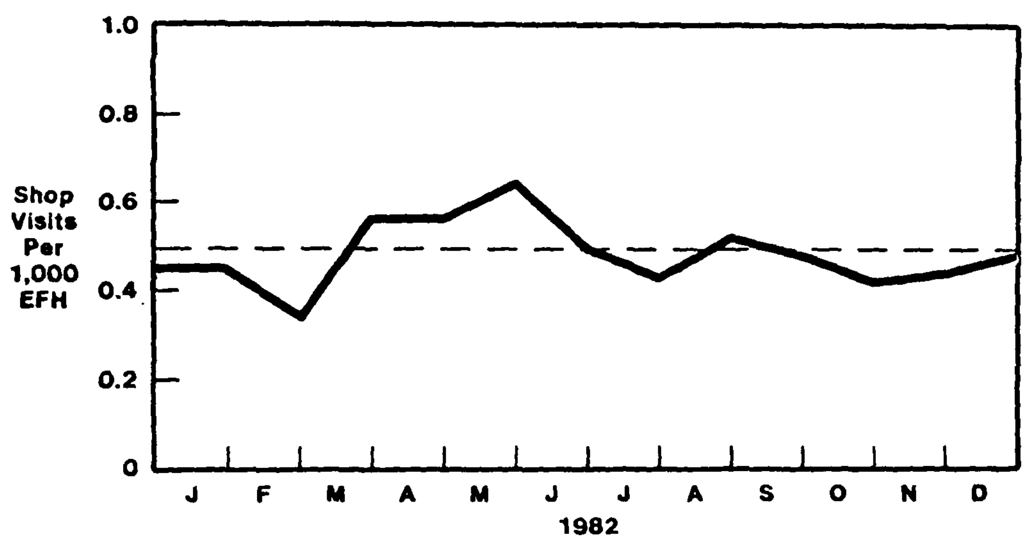
R&M FIELD DATA REPORTING/TRACKING SUMMARY

- R&M DATA TRACKED ON ALL IN-SERVICE ENGINE OPERATION SINCE FIRST UTTAS FLIGHT TEST.
- R&M DATA TRACKED/REPORTED VIA OFFICIAL RELIABILITY AND MAINTAINABILITY REPORTS THROUGH OFFICIAL QUALIFICATION PROGRAM.
- R&M DATA TRACKED/REPORTED AS BOTTOM LINE MEASURES BY T700 SERVICE ENGINEERING SINCE ENGINE IN PRODUCTION.
- ALL BLM's AND SERVICE REVEALED DISCREPANCIES REVIEWED/REPORTED TO ARMY AT PPR's/CIP REVIEWS AND TECHNICAL LETTER PROGRESS REPORTS.

IN SERVICE ASSESSMENT

The T700 has now completed one-quarter of a million operating hours. Using a 90-day rolling average, the shop visit rate during 1982 hovered around 0.5 which is GE's maturity goal for the engine. This is for all causes. Engine-caused removals account for about half of the rate, or approximately 0.25, comparable to large commercial engines. That converts to an engine-caused MTBR of approximately 4,000 hours.

T700 90-Day Shop Visit Rate



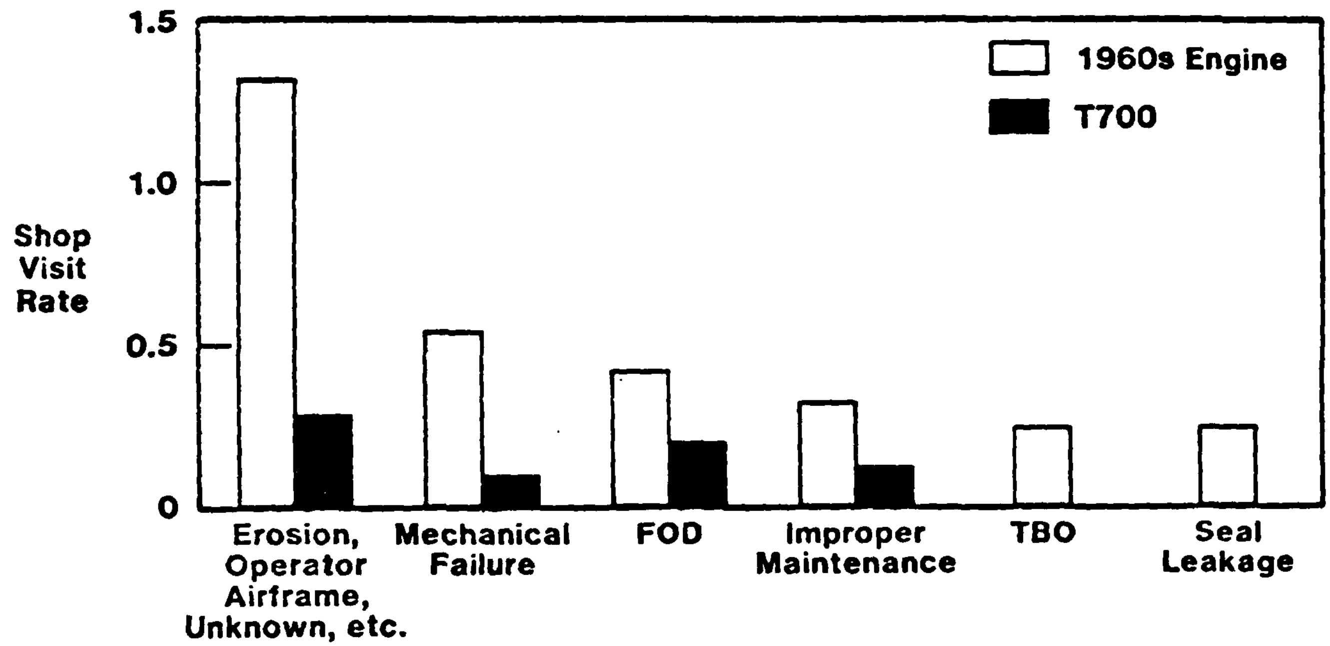
891/1-32

T700 shop visit rates for various causes generally are running from zero to 50 percent that of the earlier powerplants. It may also be noted that earlier engines had a TBO while the T700 does not because it has been "on-condition" from day one.

As with the engine, GE established a maturity goal of 1.6 removals per 1,000 engine flight hours, all causes, for LRU's. In the beginning of 1982, LRU removals were running approximately 2.0. That rate has dropped sharply and is now close to the maturity goal.

Incorrect LRU removals have been in the range of 30 to 50 percent, particularly the HMU and ECU. It has been found that the ease of removal and replacement can lead to "gang" troubleshooting rather than a logical fault-free analysis laid out for the mechanic in the engine field technical manual. Through improved troubleshooting reviews by GE's product support organization and assistance by on-site technical representatives, the "incorrect removal rate" is decreasing. In addition, a system analyzer has been developed and is now being evaluated by the Army. This analyzer is designed to isolate difficult electrical circuit faults.

Shop Visit Rate Comparison

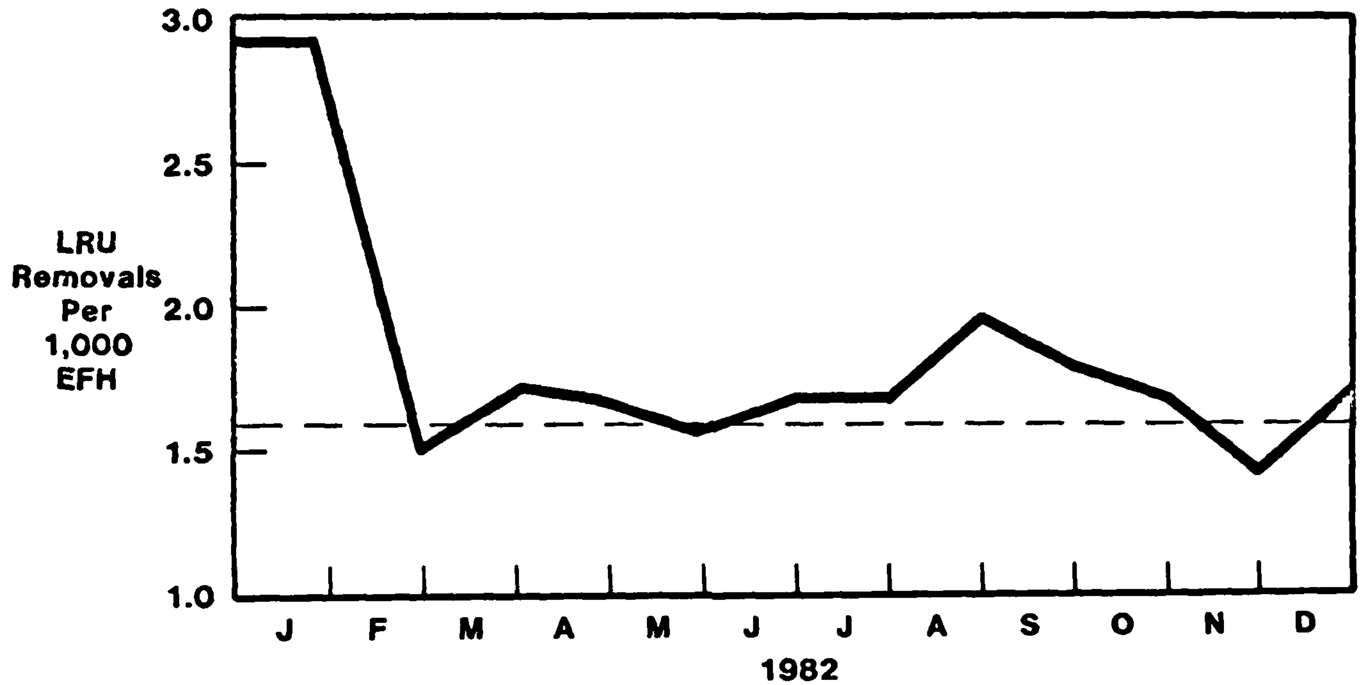


Vastly Improved Reliability — Meeting Design Objectives

T700-713(121082)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

Rolling 90-Day LRU Removal Rate

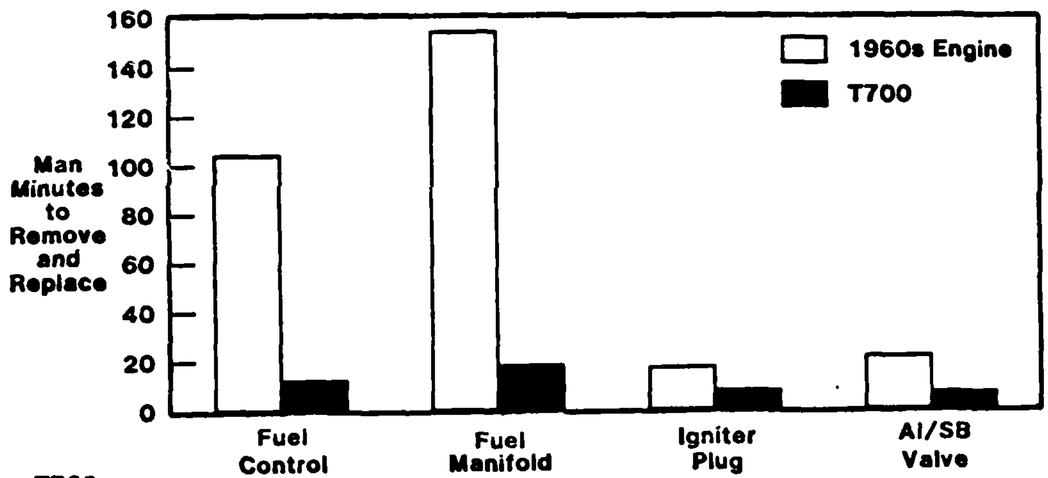


T7-820(030283)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

Flight line maintenance represents 60 percent of the maintenance actions. A comparison of the T700 to 1960's engines is shown here in terms of the man-minutes required to remove and replace four elements in the 1960's engine versus the T700.

Flight Line Maintainability Comparison



	Fuel Control	Fuel Manifold	Igniter Plug	AI/SB Valve
• T700				
— Required (MM)	22.0	—	9.0	7.0
— Actual (MM)	13.0	20.0	7.4	6.3

Approximately one man-year of corrective maintenance man-hours has been required on the T700 during its first quarter million hours of service. This includes all T700 engines at all Black Hawk operating sites.

There have even been complaints from maintenance officers about maintenance personnel losing proficiency because there is not enough maintenance activity on the T700 to keep them sharp, in spite of the fact that 2 to 3 fewer engine mechanics have been assigned to Black Hawk units than to "Huey" companies.

FIELD EXPERIENCE SUMMARY

- T700 RECORD AT QUARTER MILLION HOURS.*
  - SIX-FOLD SVR IMPROVEMENT
  - SPARE ENGINES 15% VERSUS 50%, SAVES $400 MILION
  - TOTAL LINE MAINTENANCE REQUIRED SINCE 1978 - LESS THAN ONE MAN-YEAR

*COMPARED TO MATURE PRIOR GENERATION ENGINES

SUMMARY and LESSONS LEARNED

LESSONS LEARNED

An early component design/test is needed to provide a solid base for the start of engine development programs.

<u>Demonstration Phase</u>

- Basic design concepts should be formalized/proven in advance of release of first engine hardware.
- Aerodynamics demonstration allows early initiation of mechanical design effort.
- The demonstration phase provides training for instrumentation and assembly personnel. This training is invaluable during later full scale development phase.
- The competitive nature of a demonstrator phase stimulates initiative and creativity to exceed contractual requirements in order to "Win the Program".
- A demonstrator phase proves a contractor's capabilities to meet initial government specifications/requirements.
- A demonstrator phase points out areas of concern for final design.
- A demonstrator phase can provide a nucleus of key personnel to build a sound design/development team around for the Full Scale Development Program.
- Past experience from field experience on systems to be replaced should influence new designs.

Demonstration Phase (cont'd)

- Initial concentration should be in areas that have been biggest problems for the user, i.e.,
  - FOD/erosion
  - Oil leakage
  - High Maintenance requirements
  - Low operational readiness rate
  - High removal rates
- A metallurgical engineer must be part of design team to assure proper selection of materials and to identify areas where further material development is required.
- A close coordination between design and development test organizations is essential.
- Spin pit testing should be initiated early in the program.

Full Scale Development Phase

- Maintainability features should be included in the initial prototype design to minimize redesign to final production configuration.
- Requirements should be both quantitative and qualitative.
- Requirements should push State-of-The Art.
- Realistic mission requirements should be defined as early as possible.

Full Scale Development Phase (cont'd)

- Special test equipment requirements should be included in the initial S.O.W.

- A strong design team built around key personnel from component development phase and demonstration phase can save time and preclude repeat problems.

- R&M must be designed in--it cannot be added on later.

- Maintainability engineers must be part of the design team and review all drawings before release to manufacture.

- All lessons learned during demonstrator phase should be considered for the final design, i.e.,

    - Elimination of rigging/adjustments and the use of safety wire reduces maintenance man hours significantly
    - On condition maintenance with no scheduled TBO can reduce maintenance cost.
    - Special attention is required for the high speed main shaft bearings and accessory drives
        - Close integration required with bearing vendors
        - More early lube system simulator/instrumented engine testing is necessary.
        - Fatigue testing of critical bearings to establish life is essential

- Special attention is required to assure concentricities, thermal stability and clearance control.

Full Scale Development Phase (cont'd)

- Controls and accessories require careful vendor selection.

- A manufacturing engineer must be part of design team to ensure producibility of the component before release to manufacturing is approved.

    - o Periodic design audits by senior design personnel are necessary to assure adequacy of design/incorporation of latest State-of-the-Art technology.

- Quality plans must be prepared on each component to assure compliance to design requirements to include verification of:
  - Material properties
  - Critical dimensions
  - Fit and function

- In place configuration management is necessary to maintain accurate tracking of all drawings, design changes and spec changes.

- Periodic design reviews should be conducted with the designated government program manager or systems projects office to assure interface compatibility and that engine design meets AVM requirements.

- On-site discussions and reviews by design engineers at the respective manufacturer or vendors during the initial planning and fabrication phase means fewer problems with initial development hardware.

Full Scale Development Phase (cont'd)

- 'Eyes-on' inspection of engine hardware should be performed by responsible design engineer upon delivery to provide early recognition of hardware problems.

- A Producibility Engineering Planning (PEP) team should be put into place 3 - 4 years ahead of first production delivery to audit implementation effectiveness of planning

- Properly designed test program that incorporates the following types of tests early in the program will lead to improved R&M.
  - Low cycle fatigue tests
  - Simulated environmental tests utilizing AVM installation hardware
  - Accelerated simulated mission endurance tests
  - Accelerated mission testing
  - Altitude performance/stall testing
  - Alternative fuels

- A formalized system for documenting all component and operational problems can assure recognition of problem and corrective action.

- Interface problems during the initial flight test program can be avoided if a thorough installation review is performed on every application.

Maturity Phase

- Maintainability demonstrations are needed at periodic intervals, utilizing user personnel, to assure that the design meets the need of the eventual operators.

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Maturity Phase (cont'd)

- Contractor technical representative coverage at AVM can assure expeditious identification and solution with (feedback) of early problems at AVM's.

- Incorporation of "fixes" in maturity engines is very beneficial.

- The availability of contractor technical representatives at each AVM during the maturity program will expedite the recognition of problems and their corrective action.

- A maturity program facilitates smoother transition to full rate production.

- A maturity programs allow introduction of design changes into the first production engine that lead to improved R&M.

Production Phase

- A strong production transition team in place well ahead of the receipt of the 1st production engine hardware prevents last momentum from the development and maturity phase.

- A member of the development test team on the production transition team is beneficial.

- Selection of vendors for production from development sources can improve quality.

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Production Phase (cont'd)

- Special hardware quality reviews on a scheduled basis are required to maintain emphasis on R&M.
- A periodic program review with key vendors, with emphasis on expeditious problem resolution can minimize quality problems.

Field Use Phase

- Have a member of contractor's product support team accompany government and AVM personnel on site surveys of all fielding sites at least six (6) months prior to delivery of aircraft/engines can assure that proper tooling and facilities are in place.
- Contractor technical representative must be trained and available on site at least 30 days ahead of aircraft and engine delivery to facilitate a smooth transition from production to field use.
- Instructors and key personnel training must be conducted prior to initial fielding of aircraft/engines with emphasis on troubleshooting and use of special test equipment.
- All technical publications must be validated and in place prior to delivery of first aircraft/engines.
- Special test equipment must be included in initial provisioning.

Field Use Phase (cont'd)

- If production improvement is to continue, a formalized system must be in place for documenting all field problems.

- Periodic program reviews conducted with the using organizations to review start-up problems on an expeditious basis will aid system maturation.

- Strong contractor service and design engineering team in place to resolve all start-up problems on an expeditious basis can minimize initial field use problems.

- A measurement system should be in place to collect field data to determine how well the engine is meeting original R&M requirements.

- The use of a fleet leader program in the field can aid early problem resolution.
  - Need more than one A/C and more than one location.

SUMMARY

For many years now, the MQT type test cycle has served as the standard used to qualify alternate sources. It may now be time for a new standard to be established--the AMT test cycle. This focus on AMT testing should be integrated into the Full-Scale Engineering Development Program at the outset of FSD. The objective is to achieve early maturity for the engine design during the FSD program and to eliminate or minimize the need for a follow-on Maturity Program Phase.

The T700 development program incorporated the Maturity Program concept conceived by the U.S. Army to identify and fix component deficiencies which may occur in engines that are not fully mature before entering production. This program has contributed significantly to the T700's successful field experience.

As the next generation of engine development programs begin to unfold, AMT type testing may offer the most economical and efficient means for proving engine integrity and reliability during the development phase.

Future Full-Scale Engineering Development Programs should focus on earlier AMT testing from the outset of the program. AMT testing accomplishes much more in establishing parts life integrity and exercises all parts in production to their intended field usage. AMT testing, as part of an overall engine life management program, coupled with a fleet leader program and sufficient engine usage monitors, could lead to even higher standards of engine reliability and lower life cycle costs than have been achieved in earlier programs.

SUMMARY

- MATURITY PROGRAM CONCEPT CONTRIBUTED SIGNIFICANTLY TO T700's SUCCESSFUL FIELD EXPERIENCE.

- AMT TYPE TESTING OFFERS FUTURE ENGINE PROGRAMS MOST ECONOMICAL AND EFFICIENT MEANS FOR PROVING ENGINE INTEGRITY AND RELIABILITY DURING DEVELOPMENT PHASE.

- FUTURE FULL SCALE ENGINE DEVELOPMENT PROGRAMS SHOULD INCORPORATE AMT TESTING EARLY IN THE PROGRAM.

- AMT TESTING COMBINED WITH A FLEET LEADER PROGRAM UTILIZING SUFFICIENT ENGINE LIFE USAGE MONITORS COULD LEAD TO EVEN HIGHER STANDARDS OF ENGINE RELIABILITY AND LOWER LIFE CYCLE COSTS ON FUTURE ENGINE DEVELOPMENT PROGRAMS.

- SOME TESTS SHOULD BE ACCOMPLISHED EARLIER
  - CONTROL SYSTEM/AIRCRAFT COMPATIBILITY COVERING FULL OPERATIONS ENVELOPE
  - ASMET-TYPE TESTS IN BASIC QUALIFICATION PROGRAM
  - ACCELERATED CYCLIC TESTING WITHOUT VIBRATION
  - LCF (LOW CYCLE FATIGUE)

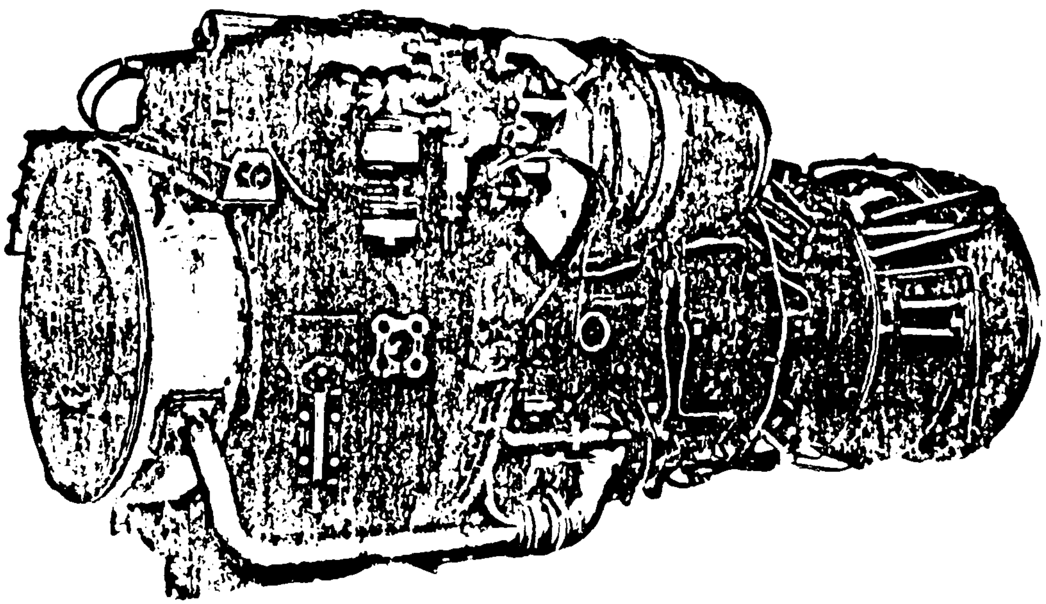
AIRCRAFT INSTALLATION TEST SIMULATION MUST BE MORE REALISTIC

ENGINE CONTROL SYSTEM/AIRCRAFT ELECTRICAL SYSTEM
- "SUITCASE TESTER" WOULD SIMPLIFY DIFFICULT TROUBLESHOOTING

PEP (PRODUCIBILITY, ENGINEERING AND PLANNING) SHOULD BEGIN EARLIER
- 3 TO 4 YEARS PRIOR TO FIRST PRODUCTION DELIVERY

MQT TEST CYCLE SHOULD BE MORE REPRESENTATIVE OF ACTUAL HELICOPTER EXPERIENCE
- MORE EMPHASIS SHOULD BE PLACED ON LCF SEVERITY

APPENDIX A
T700 Engine
Subsystems Descriptions



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ENGINE DESCRIPTION

The T700-GE-700 engine is a single-spool core, front drive turboshaft engine. It has fewer parts than any of today's comparable horsepower class engines. It features modular construction throughout and functions as a self-contained unit with many previous systems.

It has a completely integral and anti-iced inlet particle separator (IPS) plus a self-contained lubrication system with emergency loss of oil provisions including oil tank and oil cooler. The engine features condition monitoring and diagnostic maintenance provisions, has self-contained electrical ignition and control power systems and an engine-driven fuel boost pump for suction fuel capability. The water-wash system and separator are integral.

The cold section module contains three frames as part of the IPS structure, which also doubles as the oil tank, front mount and accessory gearbox support. The compressor consists of a five-stage, transonic, axial flow compressor and a single-stage centrifugal compressor connected in series and affixed to the same shaft. The axial compressor consists of four blisks (integrally bladed disks) with 3 and 4 machined on the same blisk.

The engine's hot section module consists of a two-stage air-cooled gas generator system, and a through-flow annular combustor.

The power turbine module consists of the independent, two-stage uncooled, low-pressure turbine. The low-pressure turbine shaft, which has a rated speed of 20,000 rpm, is coaxial and extends to the front end of the engine where it is connected to the AVM output shaft. There are a total of three sumps, two high-pressure turbine rotor bearings and four low-pressure turbine rotor bearings.

Basic Design

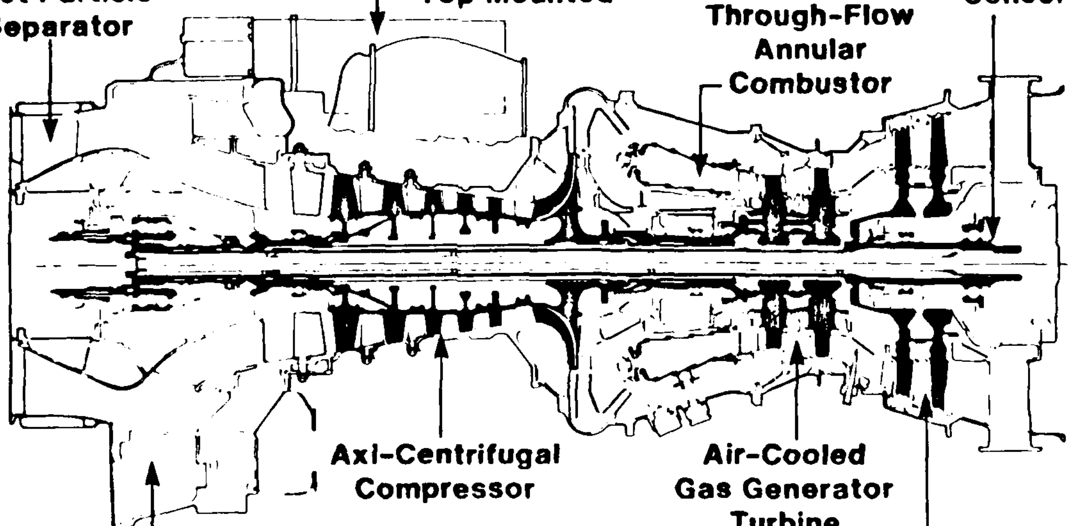


Fig. 1

T700-7(103079)

INTEGRAL INLET PARTICLE SEPARATOR

During U.S. Army Operational experience in the early '70's, turboshaft inlet separators were provided principally as airframe parts of the total installation. Most were less than satisfactory, because of operational and maintenance problems. General Electric gained much experience with inlet separators in its T58 and T64 engine installations and initiated designs in the early 1960's. It was concluded from these studies that an integral separator, using a somewhat novel approach, could be most efficiently designed as part of the engine. Moreover, performance and operation of the engine would then be solely the responsibility of the engine manufacturer.

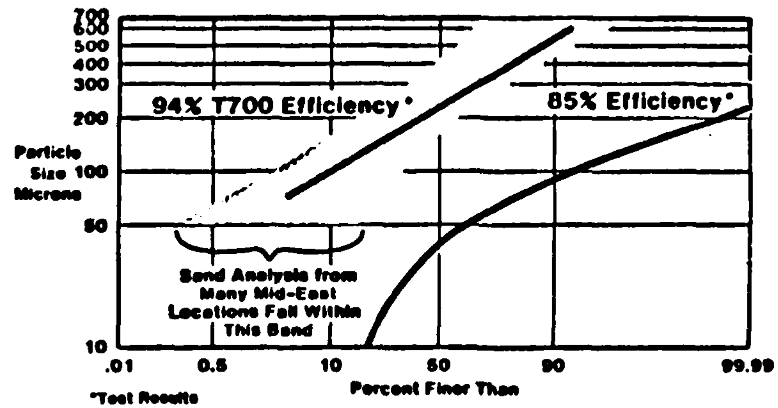
When the inlet separator is designed as an integral part of the engine rather than a bolt-on kit it can also perform several other useful functions.

The Inlet Particle Separator (IPS) is located in the Engine Front Frame. A series of non-rotating swirl vanes sets up an outward rotation of the inlet air, centrifuging out higher mass particles which are collected in an outer annular scroll. Engine air is drawn into the compressor through an inner annulus containing a set of static de-swirl vanes for minimum inlet pressure loss. The scavenge air in the scroll is drawn out by a separate engine-mounted blower (the blower specifically designed to resist erosion) and is then discharged overboard. The IPS provides the engine with an improved capability to operate in the Army field environment with enhanced safety, higher reliability, and reduced maintenance burden.

Inlet Particle Separator

- *Included in Engine*
  - Cost — Weight — Performance
- Simple
  - No Moving Parts
  - Anti-Iced

Inlet Separator Performance



AXI-CENTRIFUGAL COMPRESSOR

During the GE12 Demonstrator Program, the axial compressor stages and the centrifugal stage were developed by separate component tests and then combined in an engine for further development. The centrifugal stage has been matched to the axial stages over the entire engine operating envelope.

The all-steel compressor rotor is comprised of 11 major parts. Each axial stage is a utilized "Blisk" with blades and disk integrally manufactured from a single forging. The engine rotor includes both the axial and centrifugal component.

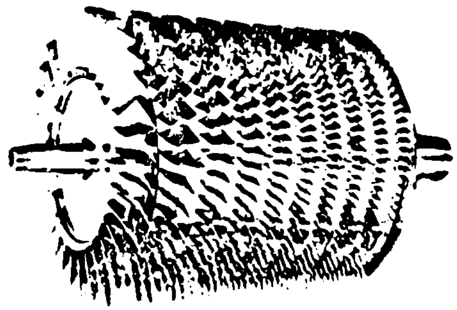
The Blisk concept of rotor construction was thoroughly tested on Stages 1 and 2 in the GE12. Since the inlet separator drastically reduces foreign object damage of the compressor, the need for individual blade replacement was not believed to be warranted. Consequently, blisks were incorporated in the T700.

The axial compressor rotor consists of a forward shaft, five blisks which form a drum-type structure similar to the GE12 Demonstrator engine, secured by curvics and tiebolt which is threaded to the forward shaft and held by a nut clamped to the aft side of the impeller.

The most notable feature of the centrifugal impeller design is the backswept characteristic of the vanes at the impeller tip. This was selected in preference to the more conventional radial impeller because of significant performance improvements.

Advanced Technology Component Design
Compressor

T58



- 10 Axial Stages, p/p 8:1
- Individual Blades
- 4 Stages Variable Stators
- Total Parts 1200

T700

- 5 Axial, 1 Centrifugal, p/p 15:1
- "Blisk" Construction
  Combined Disk/Airfoil
- 3 Stages Variable Stators
- Total Parts 216

T700 - Simple, Fewer Parts, Higher Performance

T700-991(11-77)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

The axial compressor casing is split at the 6 and 12 o'clock positions with three variable and three fixed stages. The casing has been designed to contain blade failures should they occur. The variable stator vane actuation system comprises a titanium torque shaft which is connected by an idler arm to the fuel control actuator and by turnbuckles to the actuator rings which encircle the casing. Vane levers attached to the rings and the vane spindles complete the actuation system.

The axial casing provides four bleed ports located just forward of the aft flange: two for customer bleed, one for starting bleed/anti-icing capability and another for power turbine balance piston air.

The axial compressor casing material is titanium, to take advantage of its high strength to weight ratio. The variable vanes are AM355 on Stages 1 and 2. The fixed vanes in Stages 3, 4, and 5 are Inco 718. The centrifugal impeller shroud in Inco 718 with Aluminium Silicon Coating. All blisks are AM355 material and the centrifugal impeller is Inco 718.

Sufficient spacing has been provided between the inlet guide vanes and the Stage 1 blade for bird strike capability, although the inlet separator minimizes the problem of bird strikes.

AXI-CENTRIFUGAL COMPRESSOR FEATURES

- ONLY ELEVEN MAJOR PARTS--SIMPLIFIES ASSEMBLY AND BALANCE.
- UTILIZES BLISK CONSTRUCTION--REDUCES NUMBER OF INDIVIDUAL PARTS--SIMPLIFIES ASSEMBLY/LOGISTICS.
- 5 AXIAL STAGES AND 1 CENTRIFUGAL.
- BACKSWEPT VANES ON CENTRIFUGAL STAGE FOR IMPROVED EFFICIENCY.
- SPLIT LINE AT 6 AND 12 O'CLOCK FOR EASE OF MAINTENANCE.
- TITANIUM CASING FOR HIGH STRENGTH TO WEIGHT.
- 3 STAGES VARIABLE GEOMETRY FOR MAXIMUM STALL MARGIN OVER ENTIRE OPERATING RANGE.
- ALL FIXED COMMON LINKS ON VARIABLE GEOMETRY SYSTEM TO PREVENT MISADJUSTMENT/INTERCHANGEABILITY PROBLEMS.

24172-13

COMBUSTOR

The T700 combustor is a simple, through-flow annular design utilizing proven long-life machined ring construction with central fuel injectors. The design is based on comprehensive General Electric combustor experience and the earlier GE12 engine demonstrator. The design provides high performance, long engine hot section life, low exhaust emissions and minimum field service requirements.

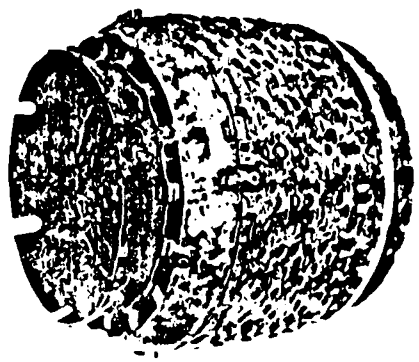
The in-line annular configuration minimizes liner surface area and provides a clean aerodynamic design which can be held to close manufacturing tolerances at reasonable cost. The central fuel injection system provides higher performance, higher reliability, insensitivity to fuel contamination and lower exhaust emissions. The small combustor volume achieved with this type of fuel injection system is conducive to a compact configuration. The combustor can operate with the following fuels:

- Type I	JP4 Referee
- Type II	JP5 Referee
- Type I	JP4 Combat
- Type II	JP5 Combat

The combustor also incorporates a step inlet diffuser which provides a predictable flow field at the combustor inlet. Another feature is a "primer" fuel system used only at low engine speeds. This compensates for lack of sufficiently atomized fuel at starting engine speeds. The system is comprised of two auxiliary fuel spray nozzles each with close-coupled electrical igniter.

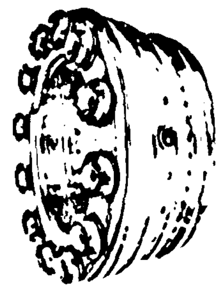
Combustor

T58



- Sheet Metal Fabrication
- 500-800-Hour Life

T700



- Simple Straight-Through Annular Design
- Durable Machined Ring
- 5,000-Hour Life

No Unserviceable T700 Combustors — Field, AMT, ASMET Proven Life

T700-1077(052281)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

At the present time no standards have been established by the Air Pollution Control Office of the Environmental Protection Agency for small turboshaft engines to be used on helicopter vehicles. It is understood that the EPA currently considers commercially operated helicopters as a minute contributor to total airport pollution. However, the emissions of Carbon Monoxide (CO), unburned fuel hydrocarbons, and oxides of Nitrogen (NO_X) will be measured and minimized by the T700 combustor design. The specification for the T700 limits the smoke emission to an SAE Smoke Number of 45 - essentially invisible for engines of this size.

Constructed from Hastelloy X, the T700 combustor system is designed to have a minimum life of 5000 hours when operated at rated temperature levels at a representative helicopter loading schedule. Within this life there is allowed 10,000 start-stop cycles, plus an additional 5000 equivalent start-stop cycles to account for cycling during the mission. Thus, the total, low cycle fatigue life is designed to be not less than 15,000 cycles.

COMBUSTOR FEATURES

- THROUGH FLOW ANNULAR DESIGN.
- PROVEN LONG-LIFE MACHINED RING CONSTRUCTION.
- CENTRAL FUEL INJECTOR SYSTEM.
- DESIGN BASED ON COMPREHENSIVE EXPERIENCE.
- PROVIDES HIGH PERFORMANCE WITH LOW EXHAUST EMISSIONS.
- PROVIDES FOR LONG ENGINE HOT SECTION LIFE.
- MINIMUM FIELD SERVICE REQUIREMENTS.
- CAN OPERATE ON WIDE RANGE OF FUELS.
- MINIMUM OF 5000 HOUR LIFE AND 15,000 LOW CYCLE FATIGUE LIFE.

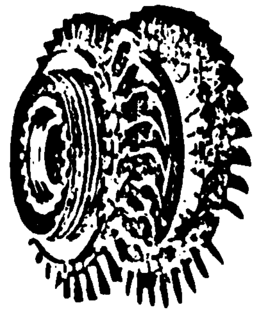
891/2-14

GAS TURBINE GENERATOR

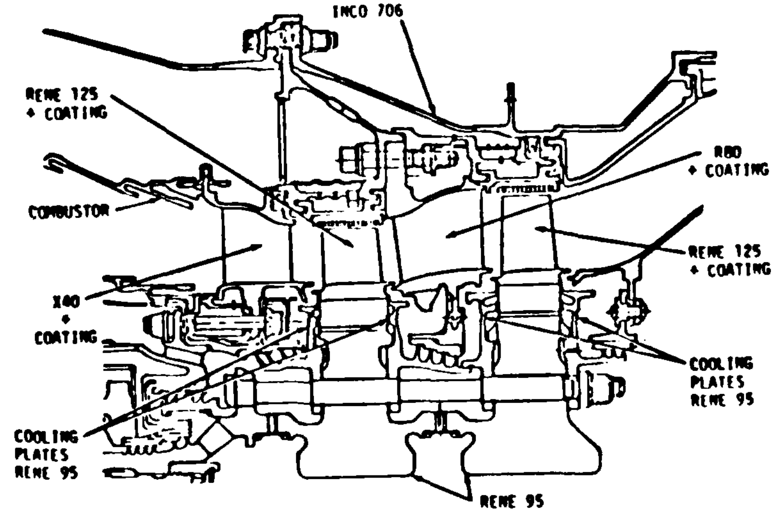
The overall design approach for the T700 gas generator turbine was to incorporate the proven GE12 demonstrator turbine with minimum design changes to meet the life, performance, maintainability and design-to-cost requirements defined by the U.S. Army. Therefore, the two-stage, air-cooled, high pressure turbine operates at the same temperature level as the GE12 and uses the same conservative cooling concepts as in the GE12. A more complicated turbine blade cooling scheme was rejected in favor of maintaining the simple radial convection system. Anticipated savings in cooling flow were marginal when compared with the greater risk, cost, and lower reliability of more complicated systems (Ref. pg. A-17). Curvic couplings between the rotor disks and forward shaft were incorporated because of significant maintainability advantages and neglibile risk of this design change from the GE12. This design allows simple field level replacement of the combustor or Stage 1 nozzle module without opening any sump or disassembly of the rotor module itself.

The turbine blades are precision castings of R125 material with a nickel-aluminide diffusion (Ref. pg. A-15) coating. Rene 125 was selected because it offers the best balance of capability in terms of rupture life and cooling flow and is already in development production for General Electric's *F101 and J101 engine hardware.*

Gas Generator Turbine



- **Two Stages**
  - Advanced Air-Cooled Design
  - GE Technology
- **High Gas Temperature**
  - High Efficiency
  - Low Metal Temperature
- **Long Life**



Gas Generator Turbine

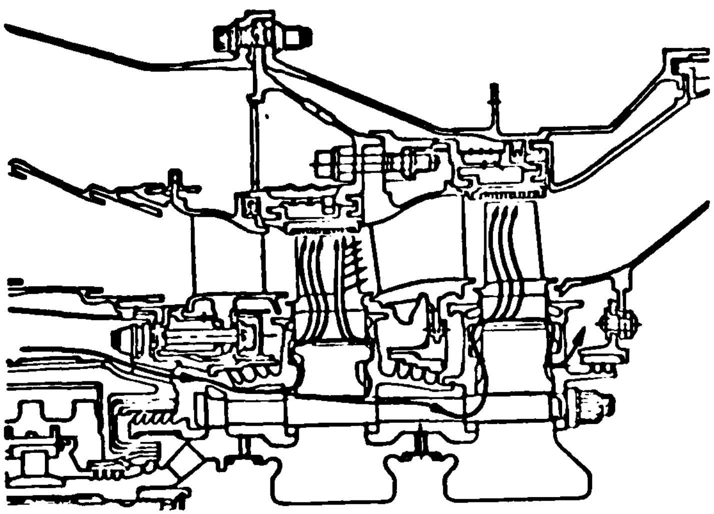
The Stage 1 blade has been slightly modified from the demo design in the tip region. The turbine blades have been designed to meet all life requirements. Life analyses have been made for the following modes:

- Stress Rupture
- Creep Extension
- Hot Environment
- Vibration Margin
- Low Cycle Fatigue

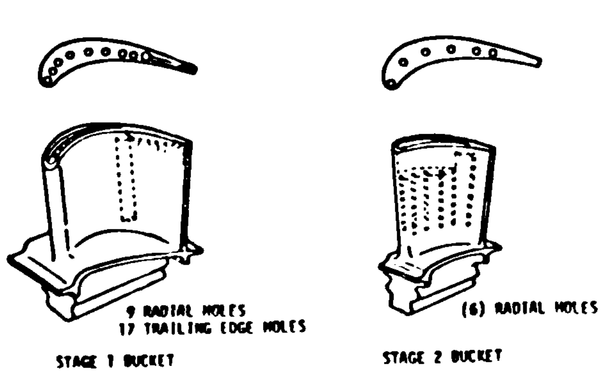
The Stage 2 blade is identical in shape to the GE12 design except for a more efficient internal tip plenum.

The Stage 1 nozzle is an investment casting of X40, an alloy which has a long history of successful casting. Stage 2 nozzles are investment cast in segments of two nozzles each in R80 material. The 100 percent rated speed at SLS, STD is 44,720 RPM. The rotor system has been designed to meet the overspeed requirement of 115 percent of maximum rated N_G limit, plus margin for burst (15 percent more).

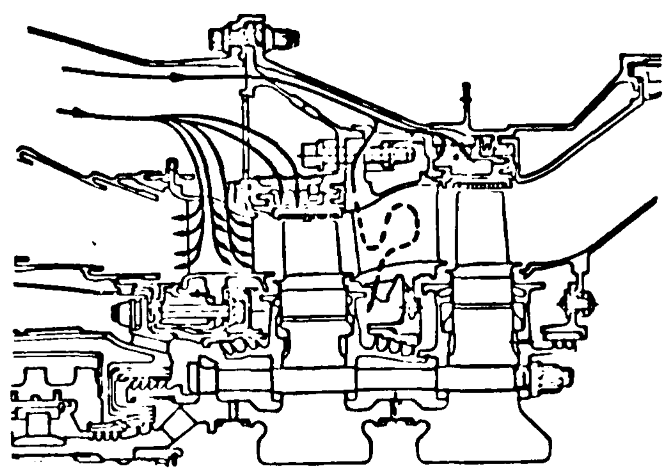
Both Stage 1 and 2 disks, cooling plates and turbine blades are securely clamped by five short tiebolts. Five larger tiebolts clamp this rotor assembly to the forward shaft through the forward curvic joint. Loosening these five larger tiebolts for rotor assembly removal will not disturb the integrity of rotor assembly itself, thus permitting simple maintenance without special tools.



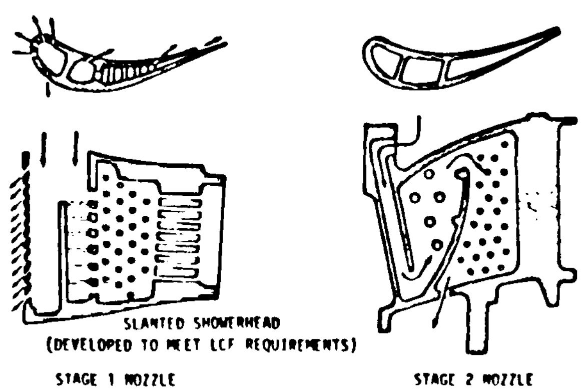
ROTOR COOLING FLOW SCHEMATIC



Gas Generator Turbine Blades



STATOR COOLING FLOW SCHEMATIC



Gas Generator Turbine Nozzle Cooling

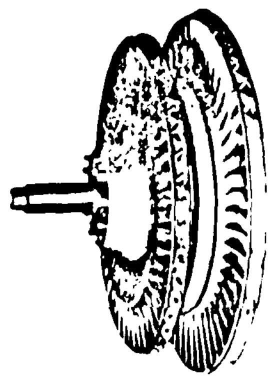
Power Turbine

The T700 power turbine is a two-stage, high-performance design with an output speed at 20,000 RPM. It followed the same aerodynamic design philosophy and has similar mechanical features as the GE12. Turbine inlet temperature for the uncooled power turbine is 1500°F+ at intermediate rated power, SLS, standard day. The general mechanical features include tip shrouded turbine blades and segmented nozzles. Simplification, reduced number of parts and material substitutions have been introduced where trade-off studies indicated payoffs in cost, maintainability, life and engine weight. The rear frame and standard exhaust system have been integrated with the power turbine to optimize performance and provide the structural integrity needed for modular maintenance. The frame struts are designed to favor 60 percent power condition with minimum chord to minimize losses during off-design high swirl conditions. To take maximum advantage of the exit swirl and its centrifugal field, the inner diameter of the exhaust diffuser is cylindrical and diffusion is accomplished at the outer diameter. The mechanical and aerodynamic features of the exhaust frame make it compatible with both a standard exhaust diffuser or an IR suppressor kit.

Power turbine life is 5000 hours including 750 hours at 100 percent intermediate rated power and with 15,000 cycle minimum low cycle fatigue life. The turbine has a minimum overspeed margin of 115 percent of max rated speed limit. The casings and outer structure provide containment in the event of blade failure. The following materials have been used in the T700 power turbine:

Stage 3 & 4 Vanes	Rene 77
Stage 3 & 4 Vanes	Rene 80
Stage 3 & 4 Discs	Inco 718

Power Turbine



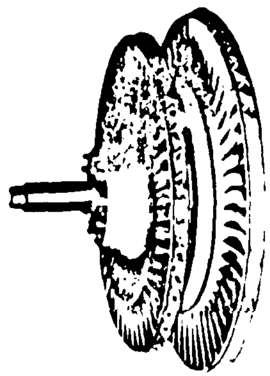
- Two-Stage Uncooled
- Tip Shrouded
  - — High Efficiency
  - — Rugged

Simple — Reliable — Proven Life

T700S-1191(082181)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

Power Turbine



- Two-Stage Uncooled
- Tip Shrouded
  - High Efficiency
  - Rugged

Simple — Reliable — Proven Life

T700S-1191(082181)

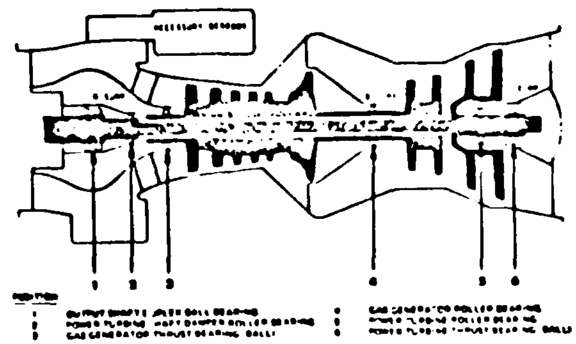
GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

Bearings and Lube System

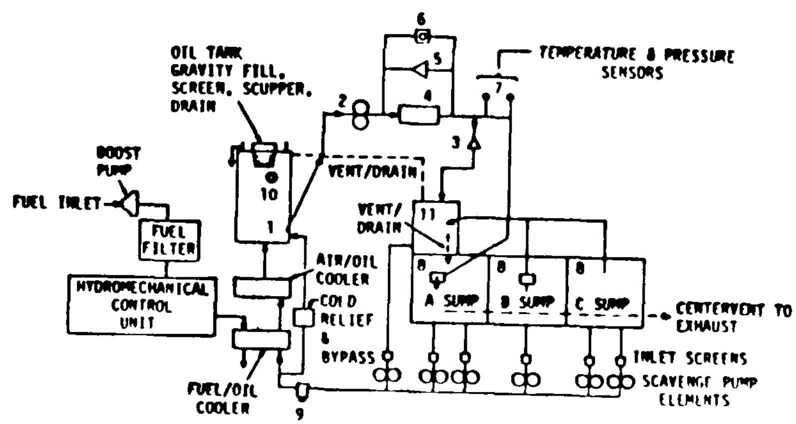
Bearing positioning for the T700 is governed by rotor dynamics. Test experience and analysis of the GE12 showed that the gas generator could be supported by two bearings No. 3 and No. 4 if each were soft-supported by springs and oil damped. The power turbine rotor requires four bearings. The No. 1 duplex ball bearing in the forward "A" sump on the output drive shaft enables the engine to withstand the thrust loads imposed by the power absorber. This bearing also supports the forward splined end of the power turbine rotor. The No. 6 aft thrust bearing ("C") sump supports the power turbine thrust load and improved radial loads. Two roller bearings, No. 2 and No. 4, serve as damper bearings and limit power turbine shaft deflections produced by either engine rotor dynamics or aircraft maneuvers. These roller bearings are soft supported by springs and are oil damped.

The general layout of the sumps result from the straight-through airflow path, the combustor design and the bearing placement.

The lube system is designed to lubricate and cool the working parts and to scavenge with minimum oil comsumption and leakage. The vent system pressures are established and controlled by the engine cycle and minimize the over pressurization and overboard oil loss associated with closed lube system design.



Bearings, Sumps and Drives Schematic



Lubrication System Schematic

Lube System Maintenance

Late 1960s Engine	T700
• Change Oil Every 100 Hours	• No Scheduled Oil Change
• Clean Filter Every 100 Hours	• Throw-Away Filter "On Condition" ~ Every 1,000 Hours
• SOAP Sample Every 12.5 Hours	• No SOAP Sample Required
• Routine Maintenance 28 MMH/1,000 Engine Hours	• Routine Maintenance 0.2 MMH/1,000 Engine Hours

T700 LUBE SYSTEM FEATURES

- 2 MAIN SHAFT BEARINGS.
- UTILIZES SPRING TYPE MOUNTING WITH OIL FILM DAMPING.
    - MINIMIZED SUMP HEAT GENERATION AND HEAT TRANSFER PROVIDING INSULATION SPACE AND UTILIZING WINDAGE TO ASSIST SCAVENGE PUMPING.
    - DUAL OIL JETS FOR LUBRICATION REDUNDANCY AT EACH MAIN SHAFT BEARING AND MINIMIZED SUSCEPTIBILITY TO PLUGGING.
    - SUMP CENTER VENTING FOR EFFECTIVE OIL SEPARATION FROM VENT AIRFLOWS
    - EMERGENCY LUBRICATION CAPABLE OF SUSTAINING THE ENGINE AT LEAST 6 MINUTES AT HIGH POWER WHEN ANY MAIN SYSTEM EXTERNAL COMPONENT IS DESTROYED.
    - INTEGRATED SUMP DESIGNS TO ACHIEVE THE DESIRED MODULAR ASSEMBLY.

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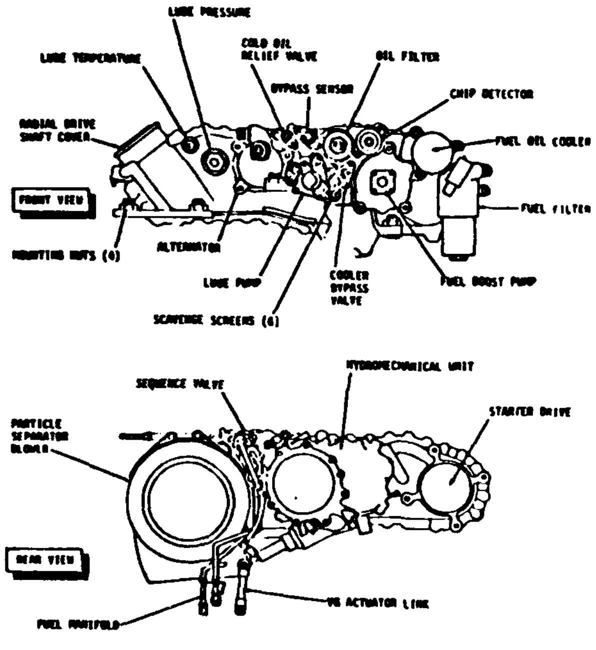
Engine Controls and Accessories

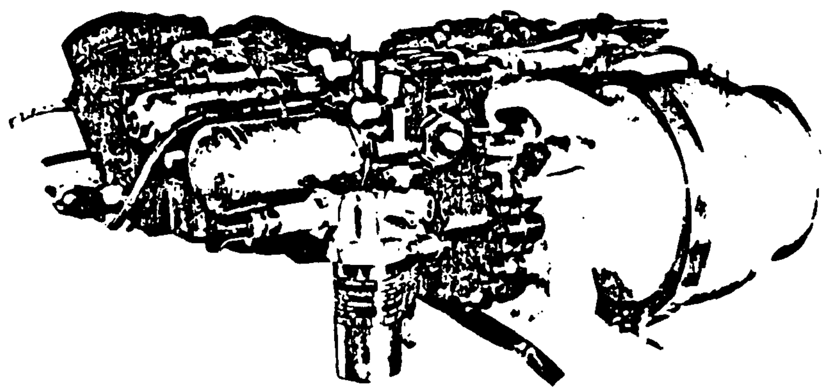
The engine controls and accessories are top-mounted which significantly minimizes vulnerability and greatly simplifies maintenance. The controls and accessories also include self-contained lube and electrical systems, and require no rigging, adjustment or matching to the engine or helicopter.

The engine control system incorporates all control units necessary for the proper and complete control of the engine (Ref. pg. A-33). The system provides for the more common functions of fuel handling, computation, compressor bleed and variable compressor stator control, power modulation for rotor speed control, and overspeed protection. The system also incorporates control features for torque matching of multiple engine installations and over-temperature protection. Rotor coordination is provided initially by a mechanical input to the control system proportional to helicopter rotor collective pitch setting. A fine trim of rotor speed control and torque matching precisely equal the rotor needs is provided electrically along with the over-temperature control.

ENGINE CONTROLS AND ACCESSORIES



Accessory Drives



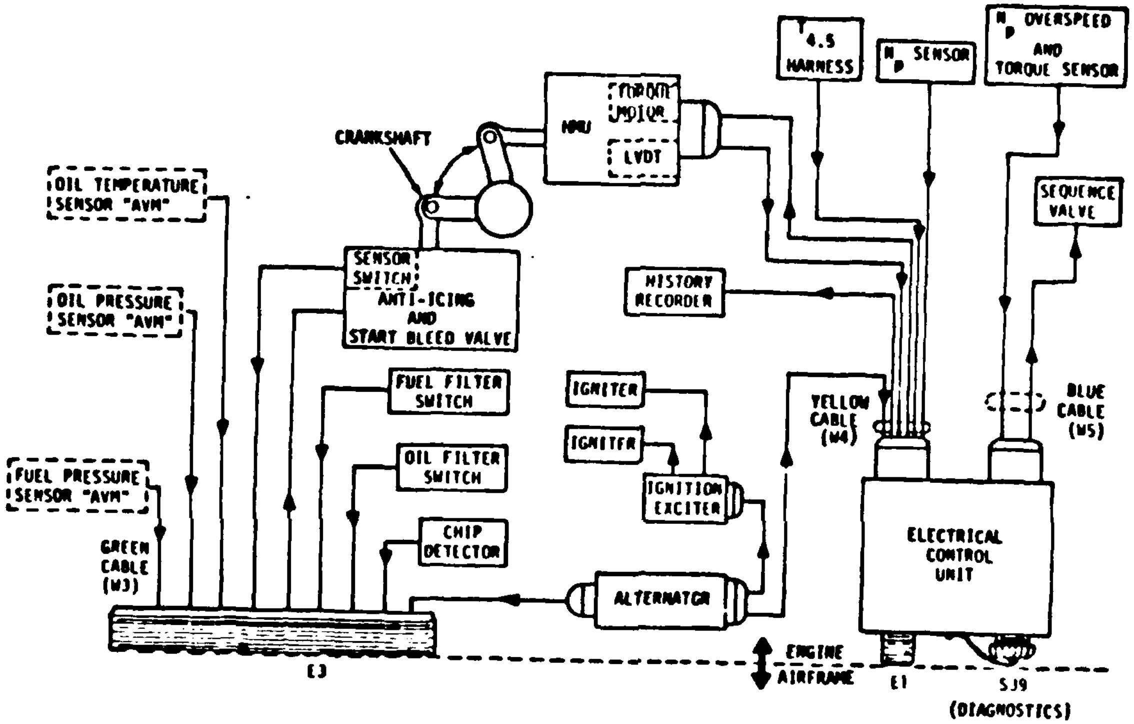
- Top-Mounted Module Includes Accessory Gearbox, Hydromechanical Control and Most Engine Accessories and Starter Pad

The hydromechanical unit is located on the aft side of the accessory gearbox. It includes a 10,000 RPM high pressure vane pump package and a closed loop variable geometry servo-actuator. A boost pump is also provided for suction feed from the airframe fuel tank, thus avoiding the normal high pressure fuel lines around the engine which have been the classic source of engine fires. There is a cleanable fuel filter ahead of the high pressure fuel pump. The fuel control incorporates a sequencing valve which distributes fuel between primer and main fuel nozzles and provides for fuel manifold draining and primer manifold purging.

The electrical control unit is located on the lower side of the engine. It resets the hydromechanical unit within acceptable limits to maintain isochronous power turbine speed governing, while automatically limiting power turbine inlet temprature. This unit also exchanges torque signals to provide automatic load sharing for multi-engine use.

An alternator is mounted on the accessory gearbox to supply the ignition exciter and electrical unit with electrical power. There is a separate ignition exciter and leads for each of the two igniter plugs.

There are, of course, thermocouple and electrical harness systems externally-mounted on the engine for main engine control, ignition and diagnostics.



Electrical System

Fuel Control

Late 1960s Engine	T700
• Up to 120 Minutes to Remove/Replace	• Remove/Replace in 15 Minutes
• Required Removal of Other Components (Pump, Filter) for Access	• Nothing to Remove for Access
• Complicated Rigging and Trim Adjustments	• No Adjustments Required

T700-772(120882)

Engine Torque System

1960s	T700
• Dual Pick-up	• Single Pick-up
• Aircraft Mounted Signal Conditioner	• Signal Conditioner Integral With ECU
• Complicated Adjustment and Calibration Procedure ~ 60 Minutes/Aircraft	• No Calibration or Adjustment Required

T700-773(120882)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

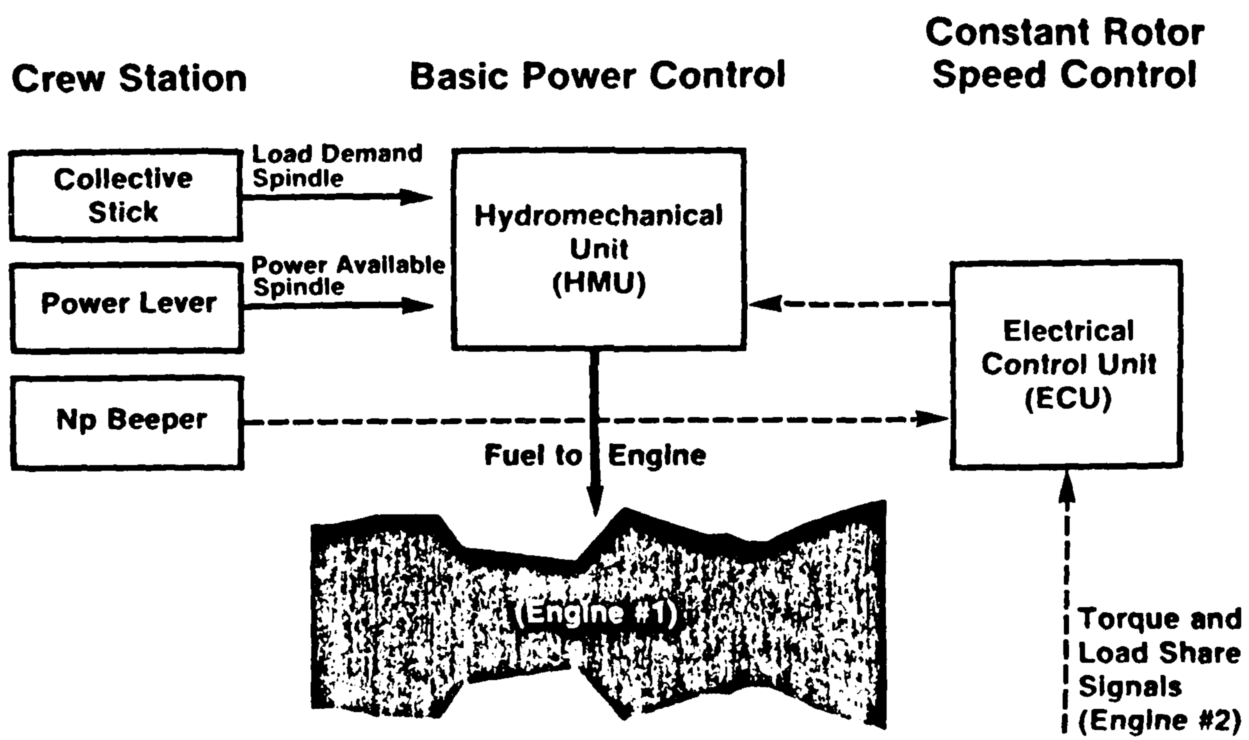
Overall

The control system was designed to be a simple system to use, requiring a low level of pilot attention. The system performs many of the controlling functions formerly performed by the pilot, allowing him to direct his attention to the prime task at hand - completing his mission. This has been done by providing:

- Isochronous power turbine and helicopter rotor (N_P and N_R) governing.
- Automatic load sharing.
- Automatic limiting of power turbine inlet temperature.
- Rapid engine transient response through collective compensation.
- Automatic Starting.

The basic system operation is governed through the interaction of the electrical control and hydromechanical units. In general, the hydromechanical unit provides for gas generator control in the areas of acceleration limiting, stall and flameout protection, gas generator speed limiting, rapid response to power demand, and variable geometry actuation. The electrical control unit trims the hydromechanical unit to satisfy the requirements of the load so as to maintain rotor speed and load sharing and also to limit engine turbine inlet temperature.

T700 Control System



T700-482(10-77)

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

THE ENGINE CONTROL SYSTEM PROVIDES:

- A STABLE, RESPONSIVE INDIVIDUAL ENGINE POWER CONTROL.
- PROTECTION OF ALL ENGINE LIMITS, AERODYNAMIC, MECHANICAL, AND THERMAL, INCLUDING POWER ABSORBER LOSS-OF-LOAD FAILURES.
- MULTI-ENGINE POWER MANAGEMENT AND STABLE HELICOPTER ROTOR SPEED CONTROL.
- ROTOR LOAD REQUIREMENTS WITH BALANCED TWIN-ENGINE POWER
- UTILIZATION OF FULL ENGINE TRANSIENT RESPONSES CAPABILITY FOR FAST LOAD CHANGES BY THE USE OF COLLECTIVE PITCH INPUT THROUGH THE LOAD DEMAND SPINDLE.
- FULL ENGINE POWER CAPABILITY THROUGH MANUAL OPERATION OF THE POWER AVAILABLE SPINDLE IN THE EVENT OF ELECTRICAL CONTROL OR POWER FAILURE.
- PRECISION CONTROL BY THE ELECTRICAL SYSTEM OPERATING AS AN AUTOMATIC TRIM TO REFINE THE MECHANICAL POWER SETTING AND TO PROVIDE ISOCHRONOUS LPT GOVERNING.
- COMPONENT INTERCHANGEABILITY WITHOUT RERIGGING OR ADJUSTMENT.
- FAULT ISOLATION CAPABILITY.

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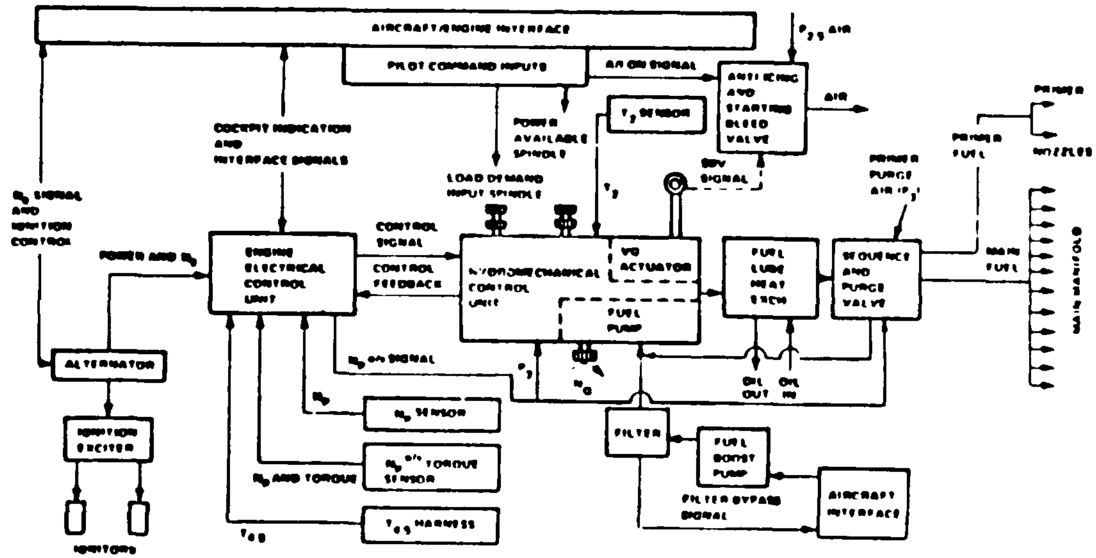

Engine Control System

MED

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